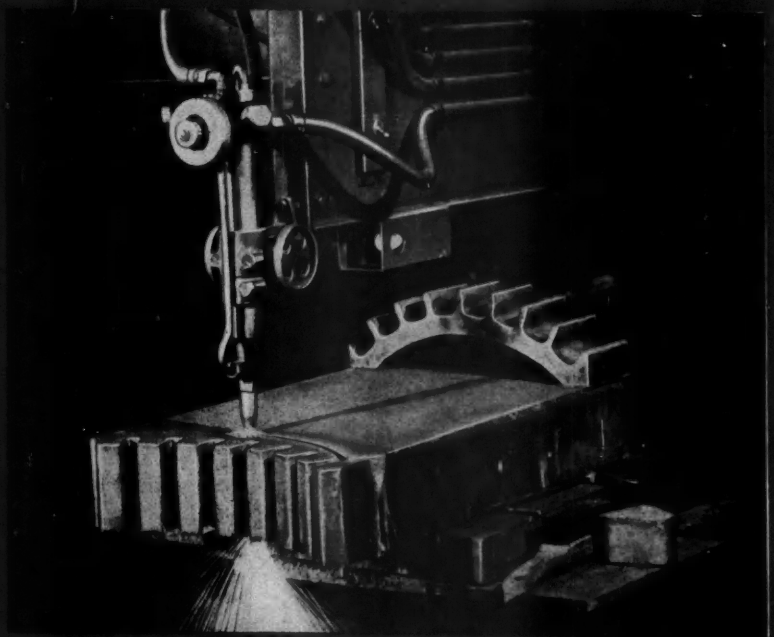
Vol. 13 No. 5 OCTOBER, 1950

E DUOBUS UNUM

TRANSACTIONS OF THE INSTITUTE OF WELDING



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'Tubewrights' welded tubular steelwork gives a high strength-to-weight ratio, a saving in steel, a low first cost, an economy in upkeep, clean contours and a good appearance.

Our engineers are ready to advise where tubular steelwork can be used to advantage, and to assist in design.

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WORKS: STAFFORD · PRESTON · RUGBY · BRADFORD · LIVERPOOL

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	EVAPORATION LB/HR	PRESSURE LB/SQ. IN.	TEMPERATURE °F
1890	3,700	100	330
1910	22,000	215	570
1930	260,000	840	850
1950	540,000	950	940

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1890

11'0"

1910

18'

1930

64'6"

1950

108'

WM

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- HIGH ELECTRODE PRESSURE
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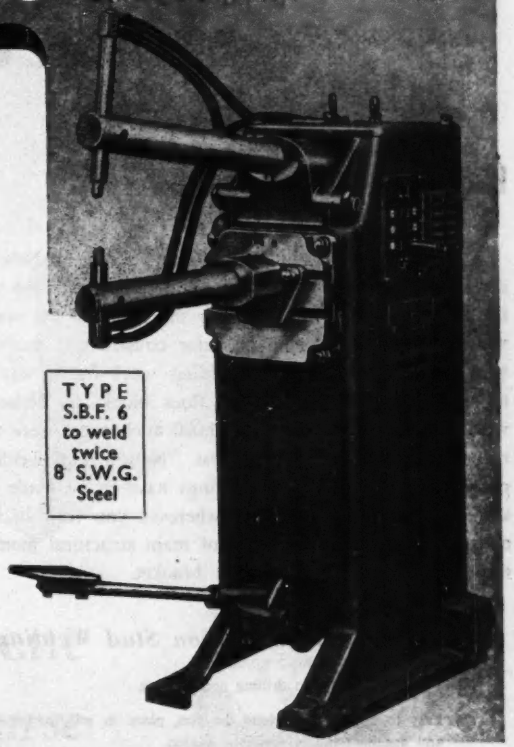
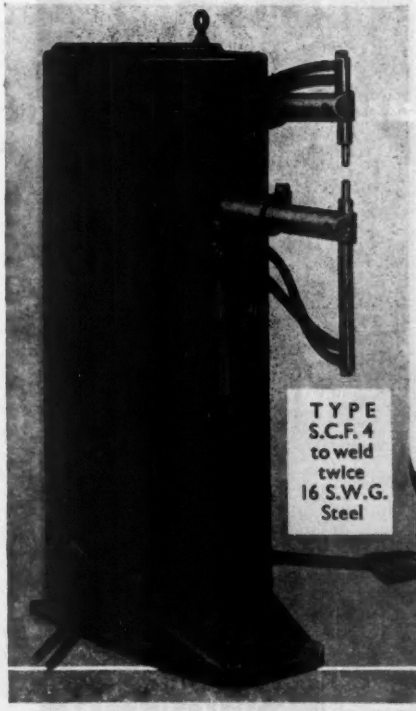
- SELF CONTAINED DESIGN
- THROAT DEPTHS 24 INS.
- ROBUST CONSTRUCTION



TYPE S.B.F. 6 to weld twice 8 S.W.G. Steel



TYPE S.C.F. 4 to weld twice 16 S.W.G. Steel

The two types of Woodhouse & Mitchell Spot Welders here illustrated are essentially practical machines designed and built for hard work and long service. Type S.C.F. 4 has two transformer capacities, viz., 7.5 and 10 KVA; and Type S.B.F. 6 has three, 20, 30 and 40 KVA. Both types have throat depths up to 24 inches.

Illustrated descriptive matter on request

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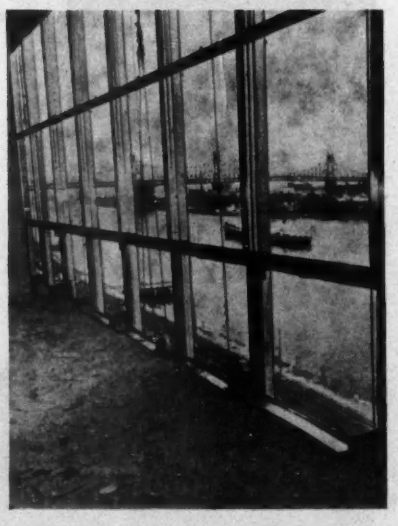
WM/1

New fixing technique speeds work on **U.N.O.** skyscraper . . .

The vast new U.N.O. Secretariat building in New York is designed with windows from floor to ceiling over the whole of the front and rear. This is why the fixing of the aluminium window frames presented a major construction problem. It was solved by Nelson stud welding—each frame was secured to steel inserts in the concrete floor blocks by Nelson studs welded on site. In this way 50,000 anchorages were made in record time and record low cost. Nelson stud welding is a proved time saver wherever fixings have to be made to steel surfaces. It has applications wherever you turn in building construction, from the joining of main structural members to the attachment of the smallest bracket.



5 points about Nelson Stud Welding

- 14 times faster than drilling and tapping.
- Easy to operate—just load the gun, place in position, press trigger and another stud is perfectly welded.
- No perforation of parent metal—you can weld Nelson studs on gas-tight or oil-tight vessels with complete confidence.
- Nelson studs are designed to ensure a good weld every time. They are end-loaded with flux and sealed over.
- Equipment comprises Nelson Gun, Automatic Timer and D.C. Welding Generator.

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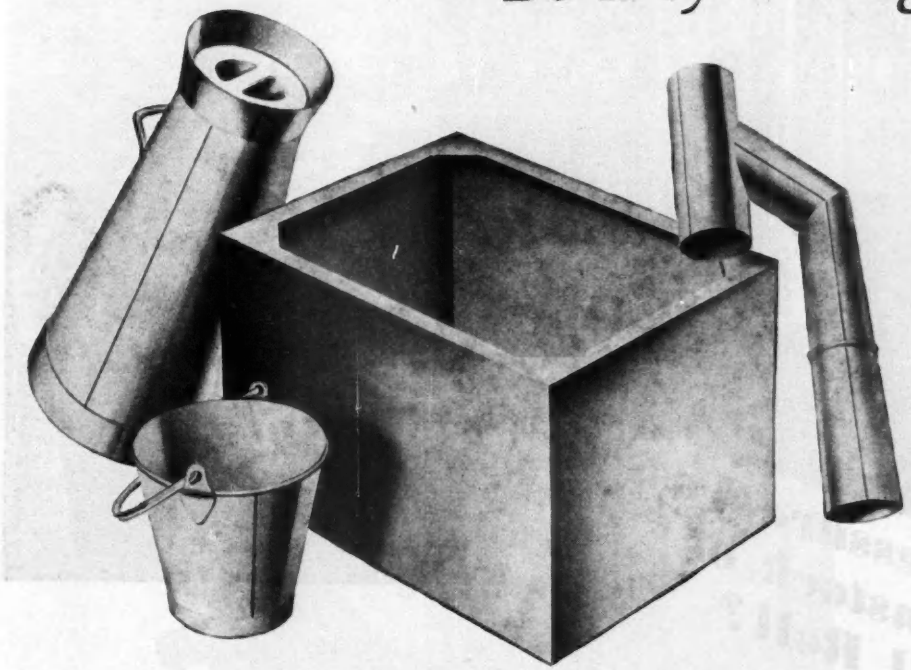
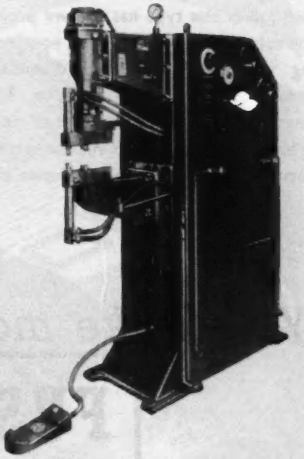
Do it by welding . . .



with M-V Equipment *of course*

Welding saves time and saves money, but it is important to start with the right equipment. Metrovick make resistance and arc welding sets and also atomic hydrogen welding equipment for special applications. In addition, M-V have themselves one of the most progressive welding shops in the country. This wealth of manufacturing and user experience is available to anyone interested in welding. Ask Metrovick, the makers who use the plant they sell.

Metrovick Standard Type "AS 60/24" Spot Welding Equipment



METROPOLITAN-VICKERS ELECTRICAL CO. LTD., TRAFFORD PARK, MANCHESTER, 17

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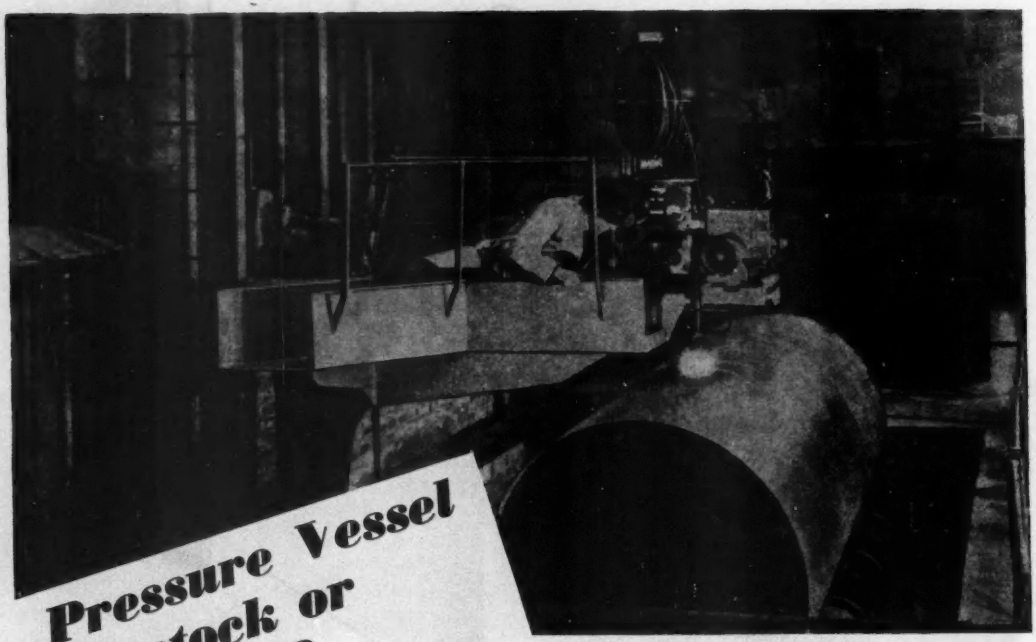
METROVICK *Equipment for More Efficient Welding*



Pressure Vessel Penstock or Mill Roll?

As specialists in welding it is, to us, just another cylindrical unit for production by automatic welding. But each job of this type has its own problems, which must be solved before it will meet your requirements. Varying weights, lengths and diameters call for modification in methods of handling. The range of equipment which we have designed and produced over a long period covers an endless variety of cylindrical forms. A typical example is shown in the photograph.

If you have a problem concerned with the manufacture of AIR RECEIVERS, BOILERS, CONVEYORS, CHASSIS MEMBERS, GIRDERS, STEEL MASTS, STEEL DECKING, PIPES, TUBES, TANKS, WHEELS, or possibly the building-up of worn surfaces on WAGON WHEELS, SHAFTS, MINING and CONTRACTORS' PLANT, etc., we shall be happy to advise you on fabrication by welding. Meanwhile, we can assure you that whatever you may be making by welding, if it's a suitable application—

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Single-Operator Welding Sets

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STRONG, COMPACT, RELIABLE
UNITS, SCIENTIFICALLY DESIGNED

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The initiative and enthusiasm which we like to think are displayed at every level in our Organisation are products of both.

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Progress and efficiency in the welding industry could not be maintained without a full knowledge of the various problems which confront welding engineers every day.

The OK ORGANISATION, because of its ability to pool the experience obtained from its factories throughout the world, is in the unique position of being able to utilise WITHOUT DELAY technical improvements and developments drawn from the widest possible field . . . all of which is reflected in the quality and range of OK Electrodes available.

Ever since Oscar Kjellberg introduced the first coated electrode in Sweden, about 1900, the OK ORGANISATION has pioneered research in arc welding, and the experience gained is gladly placed at the disposal of those who find themselves faced with a problem in selection or of application.

To all who wish to avail themselves of this service we would say . . . if there IS an answer we can think of none better equipped to produce it than the OK Organisation. . . . THE LARGEST ELECTRODE MANUFACTURING ORGANISATION IN THE WORLD.

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TRANSACTIONS OF THE INSTITUTE OF WELDING

Vice-President : PRESIDENT - C. S. MILNE *Secretary :*
HOWARD J. THOMPSON, M.I.Mech.E. G. PARSLOE, M.A.

Honorary Editor : D. S. WATT, B.Sc., M.I.N.A.

VOL. 13 NO. 5 OCTOBER, 1950 PRICE 7s. 6d.

INSTITUTE NOTES AND NEWS

Headquarters Premises.—The Council has been successful in buying the lease of the Institute's headquarters premises until 1980 at a very modest price, when compared with those asked for similar properties in the same neighbourhood. Enquiries are also proceeding with a view to the purchase of the head lease, which, if obtained, would give the Institute security in its present premises for the next forty years.

No. 2, Buckingham Palace Gardens is a house built in 1895 for private occupation. It is not perhaps ideal as office accommodation, but it is most conveniently situated in the immediate neighbourhood of Victoria Street, where so many engineering firms and institutions have their headquarters, and much can be done to adjust the building to the needs of the Institute, now that the cost of alterations and improvements can properly be spread over a comparatively long term. It has some dignity, and its principal drawback is that there is no room large enough for General Meetings there. There are, however, possibilities in the immediate neighbourhood, and the Council will certainly not miss any opportunity of obtaining a hall, if it should arise.

The purchase money is being taken from the Working Reserve Fund, contributed by members in response to the President's appeal last year, and a sinking fund is being created to replace the capital by the time the lease expires.

The President's Appeal.—The Working Reserve Fund, the appeal for which was launched in October, 1949, by Mr. O. V. S. Bulleid, now stands at more than £6,500, and something over 1,100 members have contributed. The Appeal Committee has made plans for continuing and expanding the appeal during the coming year, and before this issue appears the new President, Mr. C. S. Milne, will have sent a personal letter to the Industrial Corporate Members of the Institute, asking for their generous support.

As mentioned above, the expenses of the purchase of the lease of the headquarters premises are being met from the fund, and it would indeed have been quite impossible for the Council even to consider the offer of the lease twelve months ago, when the total reserves of the Institute amounted to £2,500 only.

The Institute is only twenty-seven years old, and its youth has been one of struggle and poverty, the regular income never much exceeding the necessary expenditure. Although all subscriptions were raised in 1947 and 1948, the advantage has largely been swept away by the continued rise in prices, and the Council is most reluctant at this time, when members in their private affairs are grappling with exactly the same difficulties as the Institute, to seek increased revenue by a further rise in subscriptions.

Yet this is a time of great opportunity for the Institute, the reputation and influence of which have been rapidly growing in recent years, so that government departments and other official bodies are looking to it increasingly for a lead in all sorts of welding questions. It is, however, impossible to finance a special conference or the publication of a technical book out of income, even although there may be reasonably good hope that the venture will in the end pay for itself. Moreover, the Council is constantly mindful of the need to improve the Library and Technical Information service and the *Transactions*, and to expand other activities. Yet all these require more capital than is at present available.

Many individual members of the Institute have taken the

FRONT COVER ILLUSTRATION.—No shape is too intricate for oxygen cutting: one profile machine may replace a number of mechanical operations. Faster and more accurate than sawing, and cutting to thicknesses impossible to shear or guillotine, oxygen cutting is indispensable for producing shapes for steel fabrication. Steel forgings, tubes, bars and other sections are cut as easily as plate—and thicknesses of 48 inches present no problem. The illustration shows a toothed rack being cut on a 55 in. B.O.C. Oxygen Cutting Machine.

THE BRITISH OXYGEN COMPANY LTD., LONDON AND BRANCHES

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The TRANSACTIONS of the Institute are issued free to Members. To non-members the price of this issue is 7s. 6d. per copy (by post 8s.). The Institute of Welding is not responsible for, and does not necessarily endorse statements made by Authors of Papers and contributors to the Discussions thereon.

opportunity to add a contribution to the Working Reserve Fund to their annual subscription this year, although they had not promised to do so. This support, which in many cases means a real sacrifice, is deeply appreciated by the Council, for it is only by such self-help that the Institute can really put itself in a position to take advantage of all the opportunities that now present themselves. What members do now for the Institute will return to them with interest in the form of improved facilities and services in the years ahead.

International Welding Congress.—Members of the Institute are invited to apply to the Secretary for forms of enrolment for membership of the International Welding Congress to be held in London and Oxford from 14 to 21 July, 1951. The forms have to be returned by 31 December next. The following is the draft programme of the Congress:

Saturday, 14 *July*	
10 a.m.-8 p.m.	Registration of the Congress members in London.
Sunday, 15 *July*	
4.30 p.m.	Meeting of the Bureau in Oxford.
6 p.m.-8 p.m.	Registration of Congress members in Oxford.
Monday, 16 *July*	
9.30 a.m.-12.30 p.m.	Meeting of the Governing Council.
2.30 p.m.-3 p.m.	Address of the President of the Institute to the Chairmen of Commissions.
3 p.m.-5 p.m.	Meetings of the Commissions, Group A.
5 p.m.-7 p.m.	Meetings of the Commissions, Group B.
Tuesday, 17 *July*	
9.30 a.m.-12.30 p.m.	Meetings of the Commissions, Group B.
2 p.m.-4.30 p.m.	Meetings of the Commissions, Group A.
4.30 p.m.-7 p.m.	Meetings of the Commissions, Group B.
Wednesday, 18 *July*	
9.30 a.m.-12.30 p.m.	"The Welding of Bridges and Structures." Special Session open to the public.
2.30 p.m.-5.30 p.m.	"The Welding of Light Wrought Alloys." Special Session open to the public.
Thursday, 19 *July*	
9.30 a.m.-12.30 p.m.	"Recent Developments in Welding in Great Britain." Special Session open to the public.
2.30 p.m.-5.30 p.m.	Meetings of the Commissions, Group A.
Friday, 20 *July*	
9.30 a.m.-12.30 p.m.	Works visit at Oxford.
2.30 p.m.-6.30 p.m.	Meeting of the Governing Council in Oxford.
Saturday, 21 *July*	
2.30 p.m.-6.30 p.m.	Visit to the Festival of Britain Exhibition, London.
8 p.m.	Banquet in London.
Monday, 23 *July-Saturday*, 28 *July*	Visits to works organised by the Branches of the Institute of Welding.

Specialist Team on Welding.—Mr. J. A. Dorrat, the Chairman of the Institute's Technical Committee, is the Institute's nominee for the team of welding specialists which left on Thursday, 21 September last, to visit works in the United States under the auspices of the Anglo-American Council of Productivity. The leader of the team is Dr. H. G. Taylor, Director of Research of the British Welding Research Association, and, as would be expected, a high proportion of the members of the team belong to the Institute. Their names are Mr. A. R. Jenkins, Deputy Managing Director, Robert Jenkins & Co. Ltd.; Mr. S. H. Griffiths, Metallurgist and Research Engineer, John Thompson Ltd.; Mr. D. C. Dixon, Director, The Cleveland Bridge and Engineering Co. Ltd.; Mr. G. S. Gowland, Assistant to Works Superintendent, Dorman, Long & Co. Ltd.; Mr. J. A. Edwards, Welding Foreman, Davey Paxman & Co. Ltd.; Mr. A. E. Cox, Welding Foreman, Hunslet Engine Co. Ltd.; Mr. H. H. Hagan, Shipbuilding Director, Lobnitz & Co. Ltd.; Mr. E. F. Newell, Secretary of Welding Sections, British Electrical and Allied Manufacturers' Association; Mr. H. E. Lardge, Chief Metallurgist, Joseph Lucas Ltd.; Mr. F. Clark, O.B.E., Superintendent, General Service Section, Sales Technical Department, The British Oxygen Co. Ltd.; Mr. H. L. Sutherst, Principal Surveyor for Port of London, Lloyd's Register of Shipping; Mr. G. A. Lockley, Technical Assistant (Welding) to Works Manager, Gorton Locomotive Works; Mr. H. E. Poole, General Secretary, National Society of Coppersmiths, Braziers and Metalworkers; Mr. E. J. Hill, General Secretary, United Society of Boilermakers and Iron and Steel Shipbuilders; Mr. W. H. Rimmer, Welder, Clarence Dock Power Station; Mr. S. M. Reisser, Constructional Engineer, Murex Welding Processes Ltd. (Secretary).

The good wishes of all members of the Institute will go with the team, and we shall eagerly await their report on the use of welding in American industrial production.

Joint Committee on Materials and their Testing.—The Joint Committee on Materials and their Testing, on which the Institute is represented by Dr. E. C. Rollason, has suggested a joint meeting with the Institute. This invitation has been welcomed by the Programme and Journal Committee, and tentative arrangements have been made for a joint meeting to be held in the Autumn of 1951. The meeting will occupy a whole day and will take the form of papers and discussion on two welding topics, namely, (*a*) "The Influence of Internal Stresses on the Capacity of a welded Structure to carry out its Duty," and (*b*) "The Effect of Welding on Brittle Fractures."

Telford Premium for Mr. Braithwaite.—The Council of the Institution of Civil Engineers has awarded a Telford Premium to Mr. R. G. Braithwaite and Mr. D. J. Davies for their paper on "Welded Highway Bridges" delivered to the Institution last year. Members of the Institute will wish to congratulate Mr. Braithwaite and will be pleased at the recognition accorded to a welding paper by the senior British engineering institution.

Mr. Braithwaite is this year the Chairman of the Midland section of the Institution of Civil Engineers.

Microfilm Edition of Transactions.—The Institute has entered into an agreement with University Microfilms, Anabor, Michigan, U.S.A., to make available to libraries microfilm copies of the *Transactions* of the Institute.

The storage and binding of periodicals present one of the most difficult problems to librarians today and a number of libraries are substituting microfilm copies for the bound files of periodicals.

Only libraries which subscribe to the paper edition are entitled to obtain microfilm copies, which are supplied at the end of the year. Libraries keep the paper copies in circulation until they begin to wear out and the demand slackens. Then the microfilm can be brought into use and the paper files are destroyed.

The cost of a microfilm copy is less than that of binding a volume in normal library style, and the space it occupies is trifling.

Enquiries about purchase should be addressed to University Microfilms, 313, North First Street, Anabor, Michigan, U.S.A.

Liverpool Branch Committee.—We regret that the name of Mr. E. F. Jefferson, a co-opted member of the Liverpool Branch Committee, was unintentionally omitted from the list published on page 104 of our June issue.

Reprints.—Reprints of the following papers published in Transactions are available at the prices named:—R. G. Braithwaite and D. J. Davies, "Welding in Bridgework and Allied Structures." Paper, illustrations and discussion reprinted from the December and February issues, Price 2s. 6d. R. Weck, "An Account of M. Henri M. Schnadt's Ideas on the Strength of Materials and his Testing Methods." Reprinted from the April issue. Price 2s.

Handbook for Welded Structural Steelwork.—A revised reprint of the *Handbook for Welded Structural Steelwork*, which has been in the press for nearly two years, is at last available, price 10s. per copy, post free. The book incorporates a number of important corrections to the formulae on pages 111-118 of the fourth edition, but is otherwise identical with that edition. It is intended to circulate the corrections to the purchasers of the fourth edition.

Binding of Transactions.—The Index to Volume 12 of the *Transactions* for the year 1949 was printed in the February 1950, issue. Arrangements have been made for the binding of members' volumes of *Transactions* in black embossed leathercloth at a cost of 10s. 6d. each, plus 1s. for postage and packing. Members wishing to take advantage of this arrangement should forward parts, with index, to Mansell (Bookbinders) Ltd., 31, Cursitor Street, Chancery Lane, London, E.C.4.

Research Supplement.—With this issue of *Transactions* is included Volume 4, No. 3, of *Welding Research*, containing the following reports of the British Welding Research Association:

R.61.—Experiments for the Determination of the Influence of Residual Stresses on the Fatigue Strength of Structures by Prof. Dr. M. Ros.

R.62.—A Review of Recently Published Information on the Spot Welding of Light Alloys by P. M. Teanby.

Reading of Papers.—Members of the Institute who would be prepared to read papers at meetings of the Institute or of its Branches are invited to forward the papers (or descriptive summaries) for consideration by the Programme and Journal Committee. Papers submitted in response to this invitation should reach the Secretary of the Institute not later than 19 November, 1950.

Examination Regulations.—Copies of the following document are available gratis to members on application to the Secretary of the Institute:—"Examination Regulations and Syllabuses."

July Examination Results.—The following candidates were successful in the Associate-Membership examination of the Institute last July:—

Sections A, B and C	C. S. Greed
Sections A and C	R. L. Fannon
Sections B and C	W. S. Hope
Section C	A. R. Smith
	A. Thomas

CENSUS OF FATIGUE FAILURES

In view of the importance of problems connected with the fatigue strength of welded structures the International Institute of Welding decided at their annual meeting at Delft in 1949 to set up a special commission on fatigue under the chairmanship of Professor M. Ros of Switzerland. At its first meeting in Paris last summer the commission decided that it was necessary as a first step to collect data available in different countries on the fatigue strength of welded joints and welded structures and on service failures of welded structures due to fatigue.

It is clear that the collection of data on service failures on an international scale will be of the very greatest value, and it is believed that a great deal of very useful information will result from this enquiry. The Institute of Welding have accepted responsibility for collecting data available in Great Britain and we appeal to all our members to communicate to the Secretary any case of fatigue failure of a welded component in service which has come to their notice. In communicating the information it is not necessary for the name of the maker of the component to appear at all, so that any report on service failure will not be linked with the name of any particular company. In submitting the information to the commission of the International Institute all references which might enable the failure to be traced to any particular machine or company will be omitted.

The information which should be given, as far as it is available, is the following:—

1. Description of part and its function, accompanied if possible by a drawing or photograph in which the location of the failure is shown or otherwise indicated.
2. Material from which the component has been fabricated (specification of steel, chemical composition, mechanical properties).
3. Welding process and welding procedure used (arc welding, gas welding, Thermit welding, flash welding, etc.). Heat treatment.
4. Specification of duty and loading of the part, if this is known.
5. Time in service after which failure occurred and/or estimate of number of loading cycles after which failure occurred.
6. Maximum stress, if this is known, at the point where failure originated.
7. Any other information, such as hardness in the vicinity of the fracture, micro-photographs, measures taken to repair failure or remedy fault.

All parts subject to many repetitions of loading are more or less liable to fatigue failure. Shafts of rotating machinery, crank shafts, parts of engine structures, gears and gear cases, parts of pumps, hoists, cranes, excavators, bridges, railway trucks, carriages, bogeys, vehicle underframes, axles, wheels and a very great number of other structures and components which are subject to repeated or fluctuating loading in service may fail by fatigue.

We appeal to all our members to communicate to us for incorporation in the British Report to the International Institute any information which will help towards making this international enquiry as complete a record as possible.

NOTES FROM THE BRANCHES

Liverpool.—The "Liverpool Branch Circular" for September, 1950, includes reports of the meetings of the Branch since last February. On 14 March last Mr. James Rainford, M.I.Mech.E., M.I.M.E., gave a lecture on "Welding as Applied to Coal Mining," a subject on which there is less literature than its importance would suggest. The lecture was illustrated with a large number of slides and two sound films, and Mr. Rainford covered every aspect of coal mining, explaining where welding entered into the construction and repair of the many varied pieces of equipment required. Among a number of questions put to the lecturer was one on the comparative costs of welding and not welding. The lecturer answered that in certain operations repairs were being done at 25 per cent. of the old costs, but that the savings were really incalculable, because welding enabled repairs to be made quickly, and so often prevented most serious stoppages in coal production.

Welded Steel Chain.—An interesting feature of the Branch Annual General Meeting was a film show, including the sound colour film "Modern Chain Making," lent by The Parsons Chain Co. Ltd. Mr. H. O. Smerd, M.Eng., Chief Development Engineer of that Company, spoke after the showing of the film. We reproduce the following summary of his remarks by courtesy of the Editor of the Branch Circular:

"All load-carrying chains must be welded to ensure the highest possible strength/weight ratio—the one notable exception being the 'weldless' chain, made by rolling and forging a length of cruciform bar into a continuous length of chain, the remaining fins interconnecting the individual links being subsequently removed by a dressing operation.

"Until comparatively recent times all welded chain had been produced by 'fire welding,' i.e. by heating the bar in the blacksmith's hearth, following by shaping and subsequent forging under the hammer. This method not only demands the greatest skill on the part of the craftsman chain smith, but also considerable physical exertion. Furthermore, this technique will yield really satisfactory results only when it is applied to best quality wrought iron. Both the latter and the highly skilled chain smiths are becoming increasingly difficult to obtain.

"On the other hand, the rapid development and perfection of modern welding processes have made it possible to produce chains, not only from various grades of steel, ranging from dead soft low carbon mild steel, to alloy steel, and even stainless steel, but also from non-ferrous alloys, as for example, Monel, which, with its extreme corrosion resistance, contributes an ideal material for use in pickling plants and certain chemical and food processing industries. It is, therefore, no longer necessary to regard certain limitations connected with the use of wrought iron as inherent properties of all chain—the dreaded cold work embrittlement being the most marked—since the progressive manufacturer, by judiciously choosing and matching the material, welding process, heat treatment and design can, in fact, produce the 'right' chain for every job.

"It is probably no exaggeration to say that every welding process has at one time or another, been applied to chain making; however, for a number of technical and economic considerations, the two otherwise most widely used processes, namely, oxy-acetylene and arc-welding, have never been successfully adapted for this purpose on a production scale.

"The two electric processes generally used in chain making are 'slow' butt resistance—and flash-welding. Apart from a certain amount of overlapping, the former method is mostly used, for the fully automatic welding of chain up to ¾ in., and in a semi-automatic form up to 1¼ in. and even 1½ in. material diameter, while the latter is being increasingly applied to the manufacture of the larger sizes, including the heaviest anchor cable.

"Since, proverbially, a chain is as strong as its weakest link, only the utmost perfection, i.e. 100 per cent. welding quality can be considered satisfactory in the chain industry, and everybody familiar with the art of welding will appreciate the amount of technical skill and of highly developed equipment required to maintain so high a standard of production combined with an output equivalent to, say, 2,000,000 welds/month.

"To be able to cope with this formidable task, the modern chain manufacturer must make full use of the most up-to-date methods of control, such as photo-electric pyrometers, electronic timers and contactors, hydraulic pressure control, etc.

"This short survey of welding in the chain industry would not be complete without mentioning the submerged arc process and the atomic hydrogen welding process with its off-springs 'Heliarc' and 'Argonarc.' One form of the submerged arc was applied during the war by a U.S. firm to the manufacture of anchor cables for liberty ships and has since been used for the manufacture of a variety of chains of medium size.

"Last, but by no means least, the atomic hydrogen process has proved an ideal method for welding individual links and components, as in the manufacture of sling assemblies and, more important still, for repair work. In fact, this highly foolproof and flexible process will eventually enable all the numerous repair depots and those of the larger users, who wish to continue the practice of servicing their own chains, to handle repairs in steel with a minimum of expenditure in capital, equipment and skilled labour, particularly since the same plant can be used for many other jobs at the same time. Also a special machine has been developed for the purpose of fully heat treating individual ('repair') links, thus ensuring that the inserted link will in every way possess the same strength as the original high tensile chain.

"The great advance in chain making which electric welding has thus rendered possible, has already led to the general adoption of steel chains in all sections of industry, mining, shipping and transport, and has also found expression in the new specification for 'High Tensile Steel Chains' shortly to be issued by the British Standard Institution."

South Western Branch.—*Visit to the Pressed Steel Co. Ltd.*—The Summer Meeting of the South Western Branch was held on 28 June last when a visit to the Cowley, Oxford, Works of The Pressed Steel Co. Ltd., was made by the kindness of the Directors. Some thirty-two members went by coach from Dursley, Bristol, Bath and Chippenham. On arrival the party split into three groups with a guide for each and made a tour of the works.

Most of the members being from small engineering works, had not realised what could be done by mass production on so vast a scale, or the planning required to ensure a smooth flow of all components through the works. Great interest was taken in the welding—electric-arc, spot welding and oxy-acetylene. The Press Shop, stamping out car body parts, was very impressive and the team work of the operators was remarkable. The tool room making the dies for the presses was a great attraction with the profile milling machines.

Lunch followed in the works and the visitors were joined by Mr. Harmsworth (Sales Manager), Mr. Moton (Chief Designer), and Mr. Simmie of the Research Department. After an official welcome on behalf of the Directors, questions were invited and members of the Branch were eager to raise them, on welding, pressing and assembly of the numerous car bodies on the production lines. Some questions were quite technical—on the composition of some of the metals used—and Mr. Harmsworth, Mr. Moton and Mr. Simmie must be congratulated on their very informative answers.

The Branch Chairman, Mr. Ford, thanked the Directors and all the gentlemen present from The Pressed Steel Co. Ltd., for their kindness, and Mr. Francis, on behalf of the members, thanked

(*continued on page* 141

REPORTS OF INTERNATIONAL WELDING COMMISSIONS

The various Commissions of the International Institute of Welding met during the week 5-10 June last in Paris, and their Chairmen submitted verbal reports of their proceedings at a plenary session there.

The International Institute has circulated reports of these meetings, some in the form of transcripts of the Chairmen's addresses and others in the form of minutes of the Commissions' meetings.

We print below a selection from these reports, which, it is thought, will be of general interest to our readers.

Commission No. 3—Resistance Welding

Vice-Chairman: J. Nègre

Commission No. 3 had the following subjects on its agenda for the 1950 session:—

1. Definition of the power of a resistance welding machine.
2. Determination of the controls recommended for spot welding machines.
3. Resistance welding terminology.

1. Power of a resistance welding machine

This study was undoubtedly the one whose completion was most urgent.

The makers in the different countries had, in fact, adopted different definitions: some gave the power as maximum short circuit power, others as the maximum power used in given welding conditions, others in terms of equivalent heat; while some adopted a duty cycle time of 50 per cent., others recommended a duty cycle of 100 per cent., and others spoke of 20 per cent.

The result of this situation was that the unfortunate industrialist who had consulted the makers in the various countries for the same clearly stated problem received suggestions for machines, the respective powers of which could not be compared with one another.

A wit even claimed that welders used rubber kVA.

Speaking seriously, it was absolutely necessary to standardise the definition of the power of machines so that it might be possible to compare the value of the machinery on the market simply by examining the stated characteristics.

The maximum short circuit power has the advantage of allowing the industrialist who wishes to put in a new machine to know the upper limit required from his power supply. This knowledge is indispensable to the electrician installing the machine. On the other hand it gives no information on the performance of the transformer. When power is expressed in terms of equivalent heat it is possible to form an opinion on the volume and weight of the transformer. However, to make comparisons easy in the first analysis, it was desirable to unify the duty cycle for which power, expressed in terms of the equivalent heat, is given. Besides, power expressed in terms of the equivalent heat gives no information on the power of the circuit required nor on the welding capacity of the machine. Bearing these considerations in mind and having studied the proposals presented by the various countries the Commission unanimously adopted the following definition:—

Definition.—A welding machine directly supplied by single phase alternate current is characterised by:

1. Its nominal power.
2. Its conventional power.

Nominal Power.—Apparent maximum power used at the highest rating, the electrodes being in short circuit and the machine adjusted so as to have the minimum of secondary impedance.

Conventional Power.—Apparent power which the machine can use for a duty cycle of 50 per cent. of the time with a one-minute cycle without exceeding the degree of heating permitted by the rules of the international electrotechnical Commission.

A further study will be required to decide upon the method for carrying out the heating test spoken of in the last definition.

Name Plates.—The Commission also decided upon the information which should compulsorily be given on the name plate of welding machines. We consider this important because knowledge of these characteristics will allow the precise possibilities of the machine to be known and the best use to be made of it.

Name plates should give the following information:—

(*a*) Name and principal address of the maker.
(*b*) Registration number of the machine.
(*c*) Nominal power.
(*d*) Conventional power.
(*e*) Primary frequency.
(*f*) Primary voltage.
(*g*) Flow of water.
(*h*) Maximum secondary current on short circuit.
(*i*) Type of insulation.
(*j*) Maximum pressure on electrodes.

2. Determinations of the welding variables recommended for spot welding machines

This again was an important problem to be solved. On the one hand many industrialists only obtained insufficient results from their machines simply because they do not know how to adjust them, while on the other hand it is extremely difficult to recommend an optimum setting in relation to the thicknesses to be welded for this may vary in accordance with many factors and particularly in relation to difficulties of accessibility.

Faced with the solution of a problem of such scope, the Commission narrowed its studies for this session to the welding of single spots on two equal thicknesses of clean mild steel, normally accessible, the thicknesses not exceeding 3·5 mm. It should be noted that the domain so defined includes the majority of spot welding applications.

Diameter of the Electrodes.—The Commission examined the values recommended by various experimenters in England (2 curves), Belgium (1 curve), United States (2 curves), France (1 curve). Agreement was easily reached because the curves are in relatively close agreement. The Commission unanimously adopted the following figures:—

0·5 = 4 mm.
1 = 5 mm.
1·5 = 7 mm.
2 = 8 mm.
3 = 9·5 mm.

With regard to the three parameters: secondary current—electrode pressure—time, the Commission considered two distinct cases: quick welding and slow welding.

Quick Welding.—The Commission studied the values recommended in England by Hipperson and Watson, in France by J. Nègre and in the United States by the American Welding Society. The practices recommended by the American Welding Society obviously have in mind the execution of very quick welds. The secondary currents as well as the pressure on the welds are important. It is, of course, true that such characteristics allow of excellent welds being carried out in the shortest times. But it must be borne in mind that the scale of European fabrications would not, in many cases, allow of the expense involved in the large

scale welding plant required if the American standards were to be complied with. On the other hand, it cannot be questioned that it is possible to obtain faultless welds with less considerable pressures and currents. In this connection we should pay tribute to the extremely interesting work of Hipperson and Watson which is supported by proofs and confirms this possibility.

The Commission unanimously adopted the figures recommended by these two experimenters for the three parameters: current electrode pressure—time. But it is essential to note that the values, current and electrode pressure, have been retained by the Commission as being the lowest limits. However, on the one hand it will always be possible to weld more quickly, though this will entail a proportional increase in the pressure and current parameters. On the other hand, the results obtained by Hipperson and Watson refer to the welding of easily accessible assemblies. In current practice, it may be necessary to assemble pieces, the accessibility of which, being more difficult, requires much stronger pressures.

Thickness	Pressure	Current	Periods
0·56	87	7·100	6
0·91	125	8·000	10
1·22	170	8·800	13
1·62	222	9·700	18
2·03	282	11·000	20
2·64	347	12·500	25
3·25	492	14·000	32

Slow Welding.—As in quick welding the Commission had retained a curve of "currents," "electrode pressures," "time" to be used in slow welding. These curves correspond to the best adjustment recommended for small welding machines, generally pedal operated, whose use is very widespread in workshops. However, since some members of the Commission had not had themselves the chance to carry out systematic tests in slow welding, the Commission decided only to present these curves provisionally while asking its members to verify them during the coming year so as to allow their official publication at next year's congress.

3. Terminology

The problem was too formidable to be completely studied during this session. Many definitions were, however, adopted and are going to be submitted to the Terminology Commission of our Institute.

In closing, may I be allowed to thank the delegates of all the countries represented on Commission 3 for the useful work which they have accomplished not only during the session but particularly in its preparation. It is this close collaboration of all concerned which has made it possible for us to accomplish useful work during the last few days.

Commission No. 4—Documentation

Chairman: First, Monsieur A. Leroy, then Mlle. L. Blosset

Present: G. A. Herpol (Belgium); A. Leroy (France) at commencement of the first session; Mlle. L. Blosset (France); M. Mosser (France); G. Parsloe (Great Britain), in part; P. D. Boyd (Great Britain) in part; G. den Hertog (Holland); E. W. Postema (Holland); I. Battigelli (Italy); Bo. F. Gorthon (Sweden); O. Matthey (Switzerland).

At the opening of the first meeting, Monsieur Leroy informed the members of the Commission that his duties as Chairman of the Commission on Standardisation, added to the responsibility of ensuring the smooth running and co-ordination of the whole of the work and meetings of the third assembly of the I.I.W., did not allow him at the same time to preside over the Paris meetings of the Documentation Commission. With the agreement of Monsieur Goldschmidt, Monsieur Leroy proposed to hand over the chairmanship to the French delegate, Mademoiselle Blosset, who had, up till then, assisted in a permanent capacity in the work of the Commission. This proposal being unanimously approved, Mlle. Blosset then took the chair and M. Leroy withdrew.

Mlle. Blosset first thanked the members of the Commission for the confidence which they had shown in her with regard to the conduct of the discussion, and then expressed her gratitude for the precious collaboration which they had been good enough to bring to the preparation of the Bibliographical Bulletin of Welding, the principle aim of the work of the Commission.

Report of Action

A report of action had been sent to all members of the Commission, consisting of an up-to-date account of the year's work, and containing remarks and suggestions about the drawing up of the Bulletin. An amendment was made to this report, regarding the division of abstracts prepared in each country: the report showed

Abstracts from Denmark	24
Abstracts from Norway	6

The total of these 30 abstracts of publications, made in the same language, was correct, but the division should read as follows:—

Abstracts from Denmark	16
Abstracts from Norway	14

Critical Examination of the Editing of the Bulletin

This examination, which took place during the meeting, took into account the five numbers of the Bibliographical Bulletin of Welding which had already appeared, and led to the following conclusions:

1. For several countries, the abstracts of the reviews were not prepared in the same country, or were prepared incompletely. It was decided that—

   France would continue to prepare the abstracts of publications of countries, permanent collaboration with whom had not yet been arranged (U.S.A., Canada, South Africa, New Zealand). Italy, thanks to a new organisation, would, in future, try to ensure carrying out the work with regard to her own publications. Switzerland would continue to supply abstracts of German reviews and would, where the work would be facilitated, send these abstracts in German. The case of publications in Spanish would later be reviewed. Steps would be taken to obtain Portuguese publications.

2. A list of all the known reviews which had not yet been abstracted and were likely to publish articles on welding would be sent to each correspondent, so that he might try to obtain abstracts for those in his own country.

3. After examining a suggestion from M. Herpol about the abstracts of bibliographical notes, new practical measures were adopted concerning the publication of references relating to detailed résumés, notably with regard to those appearing in a language different from that of the original. So as to limit the size of the Bulletin, it was decided not to cite résumés of publications which had been shortened to such an extent that they were not in themselves of any interest.

Method of Classification

1. The work of preparation of the Bibliographical Bulletin in the different countries has shown the necessity for clarifying the principles of the classification system at present used for the Bulletin. To this end, a document of about 100 pages has been prepared in France, based on the general exposé of the principles of this classification which had been drawn up some years previously when the system had been adopted. This document was distributed to those present, and would be sent to absent members of the Commission.

2. Following the decisions taken at Delft, a draft table of the references of the universal decimal classification system was drawn up by the Dutch delegate to correspond with the references of the present classification of the Bulletin. An incomplete meeting took place in this connection on 17 April, 1950, at Paris, at which were present: M. Leroy and Mlle. Blosset, France; M. Herpol, Belgium; MM. den Hertog and Postema, Holland; and M. Gorthon, Sweden. This was followed on 8 May, 1950, at Amsterdam, by discussion between the Dutch and French delegates on the practical realisation of the work. The draft prepared by Holland had been completed after the Dutch delegate had obtained from the International Documentation Federation at the Hague the necessary information about the principles governing the method of work

out new references in the universal decimal classification system. This draft was unanimously adopted by the Commission, and the Dutch delegate was asked to take steps to obtain the approval of the International Documentation Federation for the new references of the universal decimal classification system which had to be created.

Given the large number of figures for each reference in the U.D.C. system, and having regard to the financial arrangements which would have to be made to publish the complete table giving the corresponding references for the two methods of classification, it was decided to take the opinion of the subscribers to the Bibliographical Bulletin in the different countries (principally through the national institutes of welding) in order to find out how many would wish to receive this table as well as its further supplements. A delay of some months was envisaged for obtaining, on the one hand, the replies to this enquiry, and on the other, the agreement, after international consultation, of the International Documentation Federation.

According to the results received, the table would be either printed or distributed in duplicated copies from stencils made by the Nederlandse Vereniging voor Lastechniek. If printing was judged necessary, the question of including the publication of this table among the publications undertaken by the I.I.W. would be later submitted to the Governing Council of the I.I.W.

3. The creation of further subject headings, proposed by the French Institute of Welding, to meet the practical needs of subdivision in certain chapters had been unanimously accepted. These new subject headings would be published in the Bibliographical Bulletin (No. 2, April-June, 1950).

PATENTS

It was intended that steps should be taken to extend to other countries the abstracting of patents, at present undertaken in Belgium, France and Holland. In Sweden particularly the abstracting of patents could shortly be carried out, and M. Gorthon undertook to make the necessary contacts, so as to ensure that these abstracts would be furnished from the classified lists of patents existing in Sweden.

CHECKING OF REVIEWS AND DISPATCH OF DOCUMENTS

Lists of reviews publishing articles on welding (either specialist reviews or general reviews occasionally publishing articles in the field of welding) had been furnished by Belgium, the Netherlands, Great Britain and Switzerland. The correspondents of the Bulletin in the other countries were asked to draw up such lists, already arranged for at Delft, and to send them to the Institut de Soudure at Paris. It was also decided that for reviews which did not specialise in welding, but which contained an article abstracted in the Bulletin, each correspondent should send to the Institut de Soudure, wherever possible, either a copy of this review or a photostat, or a copy or microfilm of the article in question.

TRANSLATION OF ARTICLES

It was decided to draw up and to publish periodical indexes of the translations made in the various countries, mentioning the language or languages, so as to make these facts known for the use of readers who could understand the language of translation, but not the original language. This would be particularly useful for original articles published in certain languages of restricted usage, and would prevent duplication of work in the different countries.

PROPAGANDA—CIRCULATION OF THE BULLETIN

The total number of subscribers to the Bibliographical Bulletin had fallen from 1,036 in 1949, to 883 in 1950. Taking this fall into account, due to the fact that 208 subscribers in England had not renewed their subscriptions, a diminution only partially counteracted by the growth of subscribers in other countries, it was decided to take steps again for systematic propaganda work to be done in favour of the Bulletin, and for specimen numbers supplied by France to be sent out, so as to reduce the present loss incurred by the publication and paid for by the French welding organisations.

The example of the Dutch Institute of Welding which brought propaganda for the Bibliographical Bulletin to bear on a certain number of firms, could be followed in other countries.

On the suggestion of the English delegate, it was agreed to print the name of the Bulletin, and, later on, the other publications which might be produced by the I.I.W., in the national lists of welding publications. The various Institutes of Welding and editors of welding reviews should be approached in this connection by the Bulletin correspondent in their countries.

It was decided also to follow a suggestion made by Mr. Biers and brought forward by Mr. Parsloe, concerning the printing in the Bulletin of the subscription rate, as well as a suggestion for arranging with a bank in the United States for the payment there by American subscribers of the subscription amounts in dollars.

Other Business

In view of the importance of the Bulletin and the large regular increase in the number of abstracts, the possibility of bi-monthly instead of quarterly publication was envisaged. When the time came, steps would be taken by the French Institute of Welding to provide a practical solution for the publication of the Bulletin.

Reports of two U.N.E.S.C.O. conferences, at which a French observer had been present, in conformity with the decisions taken at Delft, were distributed to the members: International Conference on scientific abstracts (20-25 June, 1949); Meeting of a study group on engineering documentation (15-16 December, 1949). The last meeting of the Documentation Commission took place at the Office Central and the Institut de Soudure and was devoted to a visit and a practical study of the working of the documentation services and the drawing up of the Bulletin.

Commission No. 6—Terminology

Chairman: F. M. L. Van Horenbeeck

A wide exchange of results of scientific research and technical experiments in the field of welding makes necessary the existence of a dictionary giving the precise meaning of terms specifically connected with welding and the allied processes in the different languages in which publications of this sort are written.

The Terminology Commission has undertaken the compilation of a multilingual terminology of specific terms on welding and allied techniques.

For gas welding, electric arc welding, shapes and forms of welds, weld faults, the control of welds, oxy-cutting, welding with dissimilar metals, metallisation and surface hardening, one-language lists have already been prepared in German, English, Spanish, French, Norwegian and Swedish.

Also drafts for the correspondence between the terms, in five languages—German, English, Spanish, French and Swedish—have been prepared for the following techniques: gas welding, electric arc welding in part, shapes and forms of welds, weld faults, the control of welds, welding of dissimilar metals and metallisation.

The Commission, during the meetings held in the last few days, has examined part of these drafts, so as definitely to complete them.

Experience in the meetings has confirmed the necessity for having discussions in Commission in order to fix definitely the terms to be retained because of their specific connection with welding or its allied techniques, and in order to establish the exact correspondence between the terms in the different languages.

The Commission is thus confronted with a very serious difficulty. The number of terms to be examined is judged to be about 1,200 and during the meetings at the present annual assembly it has only been possible to discuss 150 of them. If this rate of work were maintained, ten years' work would be required to finish this first task undertaken by the Commission. It is unnecessary to say that this delay would not satisfy the Commission, and I feel that it would not satisfy the members of the other Commissions of the I.I.W. either.

The Commission has decided to take the requisite steps to speed up this rate of work. One method of work has been decided upon, so as to enable as much progress as possible to be made by correspondence between the members of the Commission during the interval between two meetings. In this way a considerable

amount of work will be prepared at the end of six months, and a new meeting of the Commission will be necessary then. The members of the Commission have unanimously expressed the wish to hold a supplementary meeting in about six months' time, so as to reach a sufficiently advanced stage by the next assembly of the I.I.W. For this extra meeting, Basle has been chosen as the most suitable geographical centre, and we have the good fortune to know already that, thanks to the great kindness of Professor Dr. Keel, director of the Société Suisse de l'Acétylène, this Association will be kind enough to welcome our Commission for the meeting.

Steps will be taken to ensure perfect unity between the terminology prepared by the I.I.W. and that standardised in the different participating countries. It is indeed indispensable that proposals for terminology made by the delegates of the different countries should exactly correspond with the terminology already standardised in their respective countries, and also that the terms which in future will be standardised in these countries correspond perfectly with the terminology already adopted by the I.I.W.

For languages spoken in several countries, the terminology will include the synonymous terms in use in these countries, with an indication of the country in which the terms in question are used.

The work at the moment covers the following nine languages: German, English, Danish, Spanish, French, Italian, Dutch, Norwegian and Swedish. It is likely that Finnish will shortly be added to this.

The Commission has sent to the Bureau of the I.I.W. resolutions concerning the following points: (*a*) relationships with the other Commissions of the I.I.W.; (*b*) contact with Germany.

Commission No. 7—Standardisation

Chairman: Monsieur A. Leroy, France

Members Present: Messrs. L. Baes (Belgium), Christensen (Denmark); Gardner (Great Britain), Ingwall (Sweden), Landragin (France), Langhoff (Finland), Miro (Spain), Zanini (Italy).

There were also present at the meeting Messrs. Duval and Gougelot, of Committee ISO/TC 44 (AFNOR).

AGENDA

(*a*) Adoption of the minutes of the Delft meetings.
(*b*) Study of the resolutions passed by ISO/TC 44.
(*c*) Comments on the work undertaken by the different technical Commissions of the I.I.W. capable of serving as a basis for international recommendations on standardisation.
(*d*) Contribution to the work of ISO.
  1. Representation by symbols of welds and definition of welding positions.
  2. Filler metals and electrodes.
  3. Arc welding material.
  4. Weld tests.
(*e*) Checking of working documents.
(*f*) Any other business.

The minutes of the Delft meetings were unanimously adopted.

1. STUDY OF THE RESOLUTIONS PASSED BY ISO/TC 44

The Committee ISO/TC 44 is the body in ISO (International Standards Organisation) empowered to study international standardisation problems which concern welding. This Committee, which met for the first time in July, 1949, at Paris, passed a number of resolutions, the text of which was available at the meeting The Commission examined these resolutions, so as to extract from them all information useful to the I.I.W.

Resolution No. 1 determines the relationship between the ISO and I.I.W. The Commission declared itself to be unanimously in agreement with the principles laid down in this resolution. It is once more underlined that the results of the technical work undertaken by the I.I.W. might be useful in connection with international standardisation, and that it is the function of this Commission to deduce from them the essentials, although standardisation work as such can only be taken up by the Committee ISO/TC 44.

Resolution No. 2 calls for no comment since the field of activity there set out covers the same subjects as those with which the I.I.W. is occupied on the level of study and technical research.

It was felt that Resolution No. 3 raised a problem of pure standardisation which the I.I.W. is not at present engaged in studying.

Resolution No. 4 raised a discussion in the course of which it was made clear that there is room for considering test methods for metallurgical products as a whole and not only for iron products. This problem also raised a general question of the standardisation of methods of testing which should be considered by the ISO.

For Resolution 5 and 5b it was made clear that Commission No. 9 of the I.I.W. (Weldability) has been specially called upon to lend its technical collaboration. This Commission had already drawn up a heavy programme at the Paris meeting, and was occupied with questions put by the ISO. In the first place, it had proposed to draw up a definition of weldability, and to carry out a check on the arrangements made in a large number of standards or specifications of different countries, with regard to the criteria chosen to appraise the weldability of common carbon steels. It would be for Commission No. 9 to see how far it could take into account the recommendations made in resolution No. 5b with regard to the future direction of its work.

Resolutions Nos. 6, 7 and 8 called for no comment, since they were concerned with problems of agreements entirely inside ISO/TC 44. In connection with Resolutions Nos. 7 and 8, it was nevertheless noted that the work of the Terminology Commission of the I.I.W. could supply a useful contribution.

With regard to Resolution No. 9, the problem was raised of knowing whether the work of the I.I.W. could contribute useful technical elements. The question seemed to be too general to be discussed as a whole. It was, however, observed that the quality of welds requires to be judged in relation to the types of welded construction and the nature of the requirements which they must fulfil (pressure vessels, bridges, structures, etc.) so that, even on the level of the ISO, connections should probably be established on this point between ISO/TC 44 and other Committees concerned with different fields of application. However, the members of the Commission were in agreement on the fact that in the case of the estimation of the density of the weld, the work of Commission No. 5 of the I.I.W. (Tests and Control) might constitute a valuable basis for international standardisation studies of the following different points:

> Definition of faults. Method of determining faults (notably for non-destructive tests). Evaluation of the quality in relation to the density.

In connection with Resolution No. 10, it was made clear that the technical help of the I.I.W. could be contributed to the work of the ISO Sub-Committees, but that it was important, in the first place, to wait until these Sub-Committees drew up their terms of reference and decided upon the questions which would be studied by each of them.

2. WORK UNDERTAKEN BY THE TECHNICAL COMMISSIONS OF THE I.I.W. CAPABLE OF BEING USED FOR INTERNATIONAL STANDARDS STUDIES. (POINTS C AND D OF THE AGENDA.)

Mr. Gardner (Great Britain) observed that, with the present organisation of the Annual Meetings of the I.I.W., it was difficult for the Standards Commission usefully to intervene with regard to the examination of the conclusions drawn from the work of the technical commissions of the I.I.W. which concern international standardisation and should be kept back for further study. Indeed, discussions on this subject had to be postponed from one year to the next, because the meetings took place simultaneously. Consequently, it was decided to hold a meeting next autumn in Paris to examine the reports on the work of the technical Commissions, and after this meeting to inform the Chairmen of the Commissions of the opinions of the Standards Commission.

Mr. Gardner also stressed the necessity for the technical commissions to concern themselves, in essence, with technical problems without concentrating their efforts on drawing up drafts for international standards. In support of his opinion, he recalled that ISO/TC 44 and its Sub-Committees were alone qualified to accomplish that task, in which national standards organisations participated.

The members of the technical commissions, although highly

qualified on a technical level, could not all equally be specialists in standardisation accustomed to the methods of work used in the drawing up of national standards or international recommendations regarding standardisation. It was, therefore, to be preferred, according to Mr. Gardner, that the contributions of the technical commissions of the I.I.W. to the work of the ISO should concern the study of specifically technical problems rather than the drafting of standards.

This opinion was shared by the members of the commission and Professor Baes thought that, at the autumn meeting of the Standards Commission, it would be possible further to clarify it in the light of the reports drawn up on the work of the technical Commissions after the meetings at present taking place.

3. Organisation of Standardisation Work

Attention was drawn to the fact that since the July meeting, the work of the ISO Committee TC 44 and its Sub-Committees did not seem to have developed. A discussion took place on the subject of the methods of work which could best and most usefully co-ordinate the activities of ISO/TC 44 and its Sub-Committees on the one hand, and I.I.W. on the other. It was understood, as Messrs. Christensen and Ingwall made clear, that it could only here be a question of simple suggestions, and this was also how the representative of AFNOR, who was present at the meeting as an observer, saw it.

It seemed to members of the Commission that the Sub-Committees of Committee ISO/TC 44 should have a chance to meet separately in the interval between the two sessions of ISO/TC 44, so as to allow them better to prepare the work of its plenary session. It is in any case clear that its method of work will finally be decided upon by the countries who have undertaken to provide the secretariats of each of the Sub-Committees, in agreement with the general secretariat. However, it was recognised that this method would have considerable advantages, particularly in the period when the Sub-Committees would have to make proposals concerning their field of activity and the order of priority of the problems to be dealt with. Mr. Gardner thought that if the Sub-Committees of ISO/TC 44 could meet respectively between then and the next meeting of the I.I.W., some technical problems could thus be put to the I.I.W. for its next meeting in 1951. It might therefore be useful to postpone the general assembly of ISO/TC 44 to 1952, which would even allow of the possibility of the Sub-Committees meeting again after the 1951 meeting of the I.I.W., so as to make further progress with their work to be submitted to the general assembly.

This view, to which no objection was raised in principle, will be forwarded to the general secretariat of ISO/TC 44 (AFNOR) asking that it should be taken into consideration.

4. Checking of Working Documents

It had been decided at Delft to undertake a permanent check of basic documents such as standards, regulations, specifications, etc., whether definitive documents or drafts. It was only possible partially to succeed in this objective, and only as far as standards were concerned. The Chairman thanked Mr. Ingwall for sending him the Swedish Codes.

The list of standards existing in the different countries was distributed, each of the members being asked to complete and correct it, and to send back his observations to the Chairman. Professor Baes at once announced modifications with regard to Belgium.

It was also decided to prepare a copy of this document in English. It would be for each of the members to make this translation directly from the original language for the standards of his own country.

The bilingual document thus drawn up would be left at the disposal of the Chairmen of the technical commissions to provide them with any documentation required in the technical work undertaken by their commission.

Commission No. 9—Weldability

Report by the Chairman, Dr. L. H. G. Geerlings

At the first meeting of the Commission on Weldability, it was decided that it was first of all essential to agree on a definition of weldability. It appeared that the definitions proposed by different countries did not differ very much. With a small modification, the following French proposal was accepted, and will be submitted to the Commission for Terminology.

"A metallic material is considered weldable to a certain degree by a given process and for a given type of application, when, by the use of precautions dependent on this degree, it lends itself to the realisation of a construction between whose elements a metallic continuity can be established by welded joints, which by their local characteristics and the overall influence of their presence, satisfy requirements specified and chosen as a base of assessment."

To assess the weldability of metals it is essential to have special tests. Until now there have been many tests but there has been no general agreement as to their suitability for different fields of engineering applications. It is the opinion of the Commission that one test applicable in all circumstances cannot be devised. Therefore, the collection of information concerning weldability tests, their field of application, practical experience, etc., will be continued by circulation of a questionnaire.

In this questionnaire the tests will be sub-divided as follows:

(*a*) tests on complete assemblies;

(*b*) tests on specimens reproducing the welding operation;

(*c*) tests independent of the welding operation.

In each category local and overall weldability will be considered.

The information collected will make it possible to compile a list from which engineers can see which test is applicable for their particular purpose.

As the study of brittle fracture is closely related to that of weldability, the Commission for brittle fractures will also be contacted.

The next subject for discussion was the specification of weldable steel. The present position was examined by reference to summary sheets of national steel standards, the data for which have been supplied by national delegates as agreed at the Delft meeting. Differences in specifications were in general not great. A sub-committee will prepare a recommendation for a general specification for weldable steel, based on the data collected. This specification can be used as a guide. It is possible that after selection and checking of weldability tests, parts of it can be omitted. It should be noted that the specification will be drafted as a guide to the engineer and not as an instruction to the steel-making industry, for their production methods.

The third subject considered was a specification for weldable stainless steels. It was agreed that proposals shall be submitted to members for tests on

(*a*) intercrystalline corrosion;

(*b*) susceptibility to cracking.

At the Delft meeting it was agreed that a study should be made of the relationship between the results of hardenability tests and the hardness and crack susceptibility of the heat affected zone of welds in low alloy high tensile steels. As the programme of the commission is already rather extensive, members preferred that for the present the Commission's work on this subject should be confined to the collection of the data available in different countries, for discussion at the next meeting.

The request for information received from the Welding Research Council (U.S.A.) was considered, and it was agreed that each

national delegate shall send to the chairman his replies to those questions on which data and experience are available in his country.

Commissions Nos. 10 and 11—

Residual Stresses and Stress Relieving

Chairman: Dr. R. Weck

Stress Relieving

The Commission completed an enquiry concerning requirements for heat treatment in different countries. The results of the enquiry will be made available in the form of a table. No research work on stress relieving has been carried out in any country during the past year, but definite proposals for such work have been formulated in Belgium concerning the effectiveness of local stress relieving by heating in sections. France will consider an investigation of the problem of local stress relieving by progressive heating. From information submitted by Dr. Forsman of Sweden, where the method of stress relieving by plastic deformation is in current use, it appears that satisfactory results have been obtained with this method over a number of years. Peening as a method of stress relieving is extensively used in the United States with satisfactory results.

Measurement of Residual Stresses

The proposal to issue a document on the measurement of residual stresses could not be brought to conclusion because the information in the possession of the Commission is not complete. A number of reports which bear on this question have, however, been submitted by Mr. Gunnert (Sweden), Prof. Soete (Belgium), Mr. Milbradt (United States) and Dr. Finn Jonassen (United States). Further information will be forthcoming from Belgium, Great Britain and the United States.

Comparison of Methods of Measurement

This work is proceeding. Six countries are participating and the test plates have been made by Great Britain and have been despatched. It is expected that the results will be available for consideration at the next meeting of the Commission.

Brittle Fracture

In a joint session with Commission No. 12 the problem of the effect of residual stresses in producing brittle fracture was discussed on the basis of a report submitted by M. Louis[1] of Belgium, concerning brittle failures in welded bridges. Although there was considerable difference of opinion on details, the general conclusion of the meeting was that residual stresses can contribute to brittle fracture under certain circumstances, and that it is, therefore, necessary for this aspect of the problem to be further investigated. Work, with this object in view, is in progress in Great Britain.

Effect of Residual Stresses on Fatigue

The effect of residual stresses on fatigue was discussed on the basis of two reports submitted by Prof. Ros[2] of Switzerland and Prof. Soete[3] of Belgium. Although the work described in these reports differed considerably in conception and execution, the same conclusions can be drawn from both investigations. Under the conditions realised in these investigations, which did not in any way inhibit plastic deformation in the test pieces used, residual stresses have been found to decrease the fatigue strength for the one million and two million cycle limits by approximately 10 per cent. In test pieces containing quite normal defects this influence may be completely masked by the effect of defects.

The Commission came to the conclusion that in assemblies larger than those tested, the influence of residual stresses may be more pronounced, especially under conditions where plastic adaptation is prevented.

In a report submitted by France on work carried out by M. G. Dawance,[4] it is shown that residual stresses exercise an influence on deformation, irrespective of whether they are due to rolling or welding. After the first loading cycle this effect disappears if the loading is not reversed.

1. H. Louis: "Cas de ruptures fragiles constatées dans la construction de ponts," *Revue de la Soudure—Lastijdschrift*, Vol. 6, No. 2, 1950, pp. 96-110.

2. M. Ros: "Experiments for the Determination of the Influence of Residual Stresses on the Fatigue Strength of Structures."

3. W. Soete (R. van Crombrugge): "Etude de la resistance à la fatigue des assemblages soudés," *Revue de la Soudure—Lasti-dschrift*, Vol. 6, No. 2, 1950, pp. 72-82.

4. G. Dawance: "Nouvelles recherches experimentales sur la plasticité des éléments de construction métallique," *Annales de l'Institut Technique du Batiment et des Travaux Publics*, Nouvelle Serie No. 130, Construction Metallique, No. 6, Mai 1950.

Commission No. 12—Brittle Fractures

Vice-Chairman: A. Goelzer

It had been decided at the Delft meetings of Commission No. 12 under the Chairmanship of Dr. Haringx, that its work should be divided between two Sub-Commissions whose studies would run parallel. The task of Sub-Commission 12a, whose rapporteur is Mr. Herbiet, is to collect, study and interpret information on fractures and on tests. Sub-Commission 12b, of which Dr. Haringx is rapporteur, is concerned with the theoretical study of brittle fractures. The object of organising the work in this way was to enable progress to be made simultaneously with experimental and theoretical subjects.

At the beginning of this session's meetings an examination of the various documents with which all the members were acquainted was carried out. The principal points brought to light by this examination are the following:

1. The majority of the documents referred to the contents recommended in the composition of steels not susceptible to brittle fracture. The importance of the report Mn/C was pointed out in particular.

2. The tests generally used to discover the susceptibility of steel to brittle fracturing are:

static tensile tests on test pieces either notched or with weld beads; impact bend tests on notched bars.

These tests are often carried out in different temperatures so as to try to determine the transition temperature.

3. Mr. de Loiris underlined the importance of the amount of potential energy stored and as a consequence the more or less great danger of susceptibility to brittle fracture according to the dimensions of a construction.

4. It should be noticed that it is difficult to obtain sufficiently precise information on concrete cases of brittle fracture. Commission 12, therefore, appeals to all its members to try to obtain the largest number of possible experimental facts.

5. Several of the documents at the disposal of the Commission mentioned the influence of all the factors concerned with the conception and execution of welded work.

Commission 12 has particularly noted the importance of not losing sight of this essential aspect of the question which was also discussed during the joint meeting of Commissions 10, 11 and 12.

This serves to remind us of the complexity of the problem—a complexity largely caused by the great number of factors which must be considered in their order of importance. It should also be kept in mind that this order may vary according to the method of construction in mind. In this connection care must be taken not to lay down too rigid criteria which would run the risk of completely paralysing one or another branch of welded construction. Therefore when a certain number of precise criteria have been arrived at, they must be carefully examined, bearing in mind the conditions imposed by the nature of the various branches of construction.

Commission 12, therefore, thinks that the problem should be prudently tackled by seeking to analyse the influence of the factors successively and entirely objectively. For this reason, during the

present session, the Commission voluntarily restricted its studies to the question for which it was best prepared; it has, therefore, tackled the task of discovering a test allowing of the compilation of a first classification of steels from the point of view of their susceptibility to brittle fracture.

In the course of a discussion directed by Mr. Herbiet for Sub-Commission "a" the Commission was in complete agreement in deciding to take into account, in order to reduce the number of tests, the following three factors:

1. Study of stresses.
2. Speed of deformation.
3. Temperature.

The various types of steel which we must try to obtain should be considered in relation to a combination of these three factors.

All the members of the Commission were also in agreement regarding the way in which these studies should be carried out so as to obtain the following experimental information:

1. Maximum strength.
2. Fracture strength.
3. Deformation corresponding to the maximum strength.
4. Deformation corresponding to fracture.
5. Energy absorbed before the appearance of the maximum stress.
6. Energy absorbed between the appearance of the maximum stress and the fracture.

These two last results come into the sphere of resilience. But we underline the fact that resilience measurements alone are insufficient.

In the light of this research plan the Commission proceeded to the examination of the various tests at present used in the different countries for the study of brittle fractures and has underlined the characteristics of these tests in a table.

In a brilliant report, Mr. Bihet, rapporteur of Sub-Commission 12b, clarified the position of new theoretical researches which are at present being, or about to be, undertaken. He made known the research plan jointly drawn up by Belgium and Holland to throw light, if possible, on the researches with which Sub-Commission 12a is concerned. He pointed out in particular that this plan envisaged a study of the common ground between the fields of elastic deformation governed by Hook's law and that of plasticity. It was made clear by common agreement that these researches would not be theoretical but experimental so as to serve as a connecting link between physics properly speaking and the study of brittle fractures by Sub-Commission 12a.

I should not complete my duty if I did not congratulate the members of our Commission and in particular the rapporteurs and secretaries on their team spirit and if I did not thank them for the great energy with which they have worked.

To conclude, I should mention that the Governing Council of the International Institute asked us to nominate a permanent European Vice-Chairman responsible for the liaison with Dr. Finn Jonassen of the United States, recently appointed Chairman of Commission No. 12. Our unanimous choice has fallen upon Dr. Haringx who so ably presided over our meetings at Delft.

BRANCH NOTES—*continued from page* 134

Mr. Ford and Mr. Masters, the Hon. Secretary, for their work in arranging the visit.

After lunch came a visit to the Research Laboratory, where the party saw many examples of the welding carried out before it is put into production. Each spot welding operation is tested and timed and the material checked. The spot welding machines in the works were then set at the required figure so that, provided all material is to standard, a good weld is bound to result. It is sometimes necessary to devise special meters, etc., in the laboratory to carry out this work. Many thousands of pounds are spent on research and many thousands more are saved by it. This tour of the Research Laboratory was the highlight of the day.

The rest of the afternoon was spent watching the motor-car bodies passing through the various stages from the assembly line, emerging shiny, painted and upholstered, ready for the engine and chassis. Members were amazed at the short time the experts took to set doors, upholster a seat, or fix the beading round windows and wind screens, compared with the struggle when one tries these jobs on one's own car. But even in this mighty factory of machines there are still a few jobs which are done better and more quickly by hand. An operator using a hand press in a huge shop of machines almost seemed out of place.

After tea at the works the party went by coach into Oxford to Christ Church. Here a guide was ready and it was a contrast from the hustle and bustle of the modern age, to see such monuments of the past. The hammer roof of the Dining Hall and the portraits of famous past students round the walls were greatly admired. A visit to the Cathedral after Evensong, when the sun was lighting up the stained-glass windows, and a visit to the kitchens to see how an ox could be roasted whole, completed a very busy day.

The homeward journey started at 7 p.m. and brought to an end a strenuous but most successful meeting.

INSTITUTE OF WELDING MEETINGS

The following is a list of Institute of Welding meetings arranged for the months of November and December, 1950, so far as particulars are available at the time of going to press:—

2 Nov. **Liverpool Branch**
Joint Meeting with the Liverpool Metallurgical Society. "Recent Work of the B.W.R.A.", by H. G. Taylor, D.Sc., M.I.E.E.

2 Nov. **Portsmouth Branch**
Film—"Stainless Steels," by J. McWilliam, M.A.

2 Nov. **Tyneside Branch**
Discussion on "Are Inspection Requirements Hampering Welding Developments?"; opened by E. Fuchs, M.A.

2 Nov. **Tees-Side Branch**
"Casting versus Welding"—open discussion with Institute of British Foundrymen.

2 Nov. **Eastern Counties Branch**
"The Welding of Plastics," by Dr. Zade (Redifon Ltd.), at Ipswich.

8 Nov. **Manchester Branch**
"Design of Pressure Vessels," by E. F. Burford.

9 Nov. **South London Branch**
"The Status of the Welding Engineer," by J. H. Paterson, D.Sc., F.R.I.C., at Institute of Marine Engineers.

10 Nov. **Birmingham Branch**
"Some Welding Reminiscences to Promote Discussion," by F. Clark, M.B.E.

10 Nov. **East Midlands Branch**
Films—"The Manipulation of Corrosion and Heat Resisting Steels" and "Some Applications of Firth Vickers Special Steels," introduced by J. McWilliam, M.A., at Leicester.

10 Nov. **East of Scotland Branch**
"Welding of Non-Ferrous Metals," by D. W. Wright, at Dundee.

10 Nov. **South Western Branch**
Subject: Not yet known.

14 Nov. **Sheffield Branch**
"Recent Advances in the Welding of Non-Ferrous Metals," by W. K. B. Marshall, B.Eng.

15 Nov. **Wolverhampton Branch**
Institute Luncheon at the Café Royal, Regent Street, followed by film show (4 p.m.) and paper (6 p.m.) at the Institution of Civil Engineers. Lecturer: Professor Dr. Ing. E. Torroja. Subject: "Welded Bridges and Hangars in Spain." "Recent Developments in the Metallurgy and Weldability of Austenitic Steels," by E. Bishop, B.Sc.

15 Nov. **West of Scotland Branch**
"Welding of Corrosion and Heat Resisting Steels," by J. McWilliam, M.A.

18 Nov. **Southampton Branch**
"The Weldomat Process," by R. L. Gaughan.

21 Nov. **Liverpool Branch**
Film Show.

23 Nov. **Leeds Branch**
"Oxygen in Steel Work," by T. Humes. Film and discussion.

30 Nov. **North London Branch**
"The Welding of Cold Rolled Steel," by W. Mackenzie, M.Inst. R.A., at the Regent Street Polytechnic.

1 Dec. **Eastern Counties Branch**
"The Welding of Pressure Vessels," by E. F. Burford, at Colchester.

5 Dec. **East Midlands Branch**
"Post-War Developments of Arc Welding Electrodes in this Country," by R. L. Gaughan, at Nottingham.

6 Dec. **Manchester Branch**
"Distortion in the Welding of Mild Steel," by A. V. Houston.

6 Dec. **South London Branch**
"Metallurgy and the Welder," by P. L. J. Leder, M.Sc., A.I.M., at Institute of Marine Engineers.

7 Dec. **Tyneside Branch**
"Argon Arc Welding, by R. R. Sillifant.

7 Dec. **Portsmouth Branch**
Subject: Not yet known.

7 Dec. **Tees-Side Branch**
"Automatic Welding."

7 Dec. **Birmingham Branch**
Annual Dinner at Grand Hotel.

7 Dec. **Eastern Counties Branch**
"The Fabrication of a 280 ft. Excavator Boom," by E. McMinn, at Norwich.

8 Dec. **South Western Branch**
"Metal Spraying and its General Applications," by J. H. Payne.

8 Dec. **Birmingham Branch**
"Fabricating for the Electrical Engineering Industry," by H. H. Reeve.

9 Dec. **Tyneside Branch**
Annual Dinner.

12 Dec. **Liverpool Branch**
"The Developments and Progress of Machine Welding in Britain," by H. J. Stretton.

12 Dec. **Sheffield Branch**
"The Welding of Gas-Turbine Steels," by E. Bishop, B.Sc.

13 Dec. **Wolverhampton Branch**
"Production Welding," by A. E. Griffin.

13 Dec. **West of Scotland Branch**
"Welding in Tanker Construction."

14 Dec. **Leeds Branch**
Staybright Films 1 and 3—J. McWilliam, M.A.

14 Dec. **North London Branch**
"The Welding of Heavy Machine Parts," by C. E. Moore, at Enfield.

19 Dec. **East of Scotland Branch**
"Metallurgy for Welders," by Dr. S. J. Bennet, at Dunfermline.

THE WELDABILITY OF CHROMIUM-MOLYBDENUM STEELS.

STEEL COMPOSITION AND ARC WELDING PROCEDURE.

By H. F. Tremlett, A.R.S.M., F.I.M.*

In this paper, delivered to the Tyneside Branch of the Institute, after introducing the chromium-molybdenum pipe steels, ½ per cent. Cr-Mo, 2¼ per cent. Cr, 1 per cent. Mo and 5 per cent. Cr-Mo, reference is made to the use of these alloys in the form of relatively large welded plate vessels or structures in the oil refining industry. The arc welding of alloy steels of this type, in plate form, calls for control of welding procedure to prevent cracking in the welded joint and to produce adequate ductility. Furthermore, there is scope for the steelmaker to assist the fabricator by controlling the composition so as to enable relatively simple welding procedures to be adopted. Both these points have been studied. Using the Reeve Fillet Weld Test and determining the effect of factors such as pre-heat temperature, carbon content, electrode composition, etc., a suitable welding procedure to give freedom from cracks and reasonable joint ductility was determined for each steel. Also a preferred limiting carbon content for each type was selected.

Introduction

WHEN molybdenum is added to mild steel, its ability to resist deformation under continued load at high temperature is increased. In other words it becomes a "creep resisting" steel.

If chromium is added the steel develops resistance to scaling at high temperatures and also to attack by hydrogen sulphide, elementary sulphur and organic sulphur compounds.

These properties are necessary in the materials used in oil refining, and we find that tubes of chromium-molybdenum steel with varying amounts of chromium up to 5 per cent. are used extensively in that industry.

The main purpose of this paper is to consider the weldability of these steels in plate rather than tube form, since the requirements of resistance to corrosion and scaling and strength at temperature can also apply to the materials of large vessels in which the various chemical processes are carried out.

In fabricating such vessels the problems of weld cracking are likely to be more evident than in tube welding, since the welding process is, for practical reasons, restricted to arc welding and the conditions of rigidity at the joints are more severe.

The purpose of the work described in this paper is to assess by means of a standard crack sensitivity test the weldability of the 1 per cent. Cr-Mo, 2¼ per cent. Cr-Mo and 5 per cent. Cr-Mo steels and to determine welding procedures and limits of composition which will enable sound joints to be made under very severe conditions of rigidity.

It is generally known that steels which are subject to cracking when welded at normal temperatures may be rendered immune to this by pre-heating. When large vessels are to be constructed the practical problem of pre-heating is magnified greatly as the required pre-heat temperature is raised substantially above 200 deg. C. It is, therefore, of considerable practical importance to know the minimum pre-heat temperature that will prevent cracking. It is evident that trial and error methods on large assemblies are likely to be expensive so that the metallurgist turns to laboratory tests for the required information. This method of attack is to try to weld samples of the proposed steels under conditions of rigidity which he has reason to believe will equal in severity, if not actually exceed, those in the full scale weldment.

A laboratory welding test which has come to be regarded as complying with these requirements is known as the Reeve Fillet Weld Test. This was developed by Dr. L. Reeve of the Appleby-Frodingham Steel Co. Ltd. in order to study the weldability of various alloy high tensile steels. A full description of these early researches into this subject appears in a paper entitled "Metallurgical Aspects of the Welding of Low Alloy Structural Steels," by T. Swinden and L. Reeve, in *Transactions*, Vol. 1, 1938.

Various modifications of the original test have been used for later work, but the essential principle of maximum rigidity of joint remains. The severity of the test has led to the criticism that it exceeds the degrees of rigidity commonly met in practical construction, but, from the point of view of confidence in the usefulness of the results, this is an error in the right direction.

Slight modifications of this test have been used to determine the crack sensitivity of the chromium-molybdenum steels and to observe the effect of pre-heat, electrode composition, carbon content of the steel, etc., on weld joint ductility and crack sensitivity.

The information so obtained, together with that provided by a metallurgical study of the welded joints, enables welding procedures and steel compositions to be selected in a manner to help the fabricator to deal with the welding problems which cannot be avoided.

SECTION 1

Statement of the Problems Raised in the Arc Welding of Cr-Mo Steel Plates

Low alloy steels, of which the Cr-Mo series form a compact group, are "difficult" for welding, owing to the fact that, with slipshod procedures, it is comparatively easy to produce joints which are defective due to internal cracks. If very high pre-heating temperatures are used and procedures carefully controlled there is no risk of cracking, but such methods, while possible with pipes or small vessels, are not always practicable. Accumulated knowledge of the factors influencing weld joint cracking in low alloy steels suggests that the elaborate heat treatment procedures, recommended by certain authorities for welding Cr-Mo steels, may not, in fact, be essential. The problem then becomes one of making a joint free from cracks and with sufficient ductility to withstand handling into a stress relieving furnace, though such a joint may not be in a condition of maximum softness prior to stress relief. It is admitted that this question of the necessary ductility to be left in the joint before stress relief is one that does not lend itself to quantitative treatment. If, however, it is appreciated that the joints are in a state of stress and with only limited ductility due care will be taken in moving the vessel into the stress relieving furnace.

This leads to a consideration of the type of electrode to use. Partly owing to the spectacular success achieved in the welding of armour plate with austenitic chromium-nickel electrodes, which are basically of the stainless steel type, and partly owing to experience in other fields, it is recognised that a great measure of success can be obtained with these electrodes on almost any type of steel which tends to harden as a result of metallurgical changes

* The United Steel Companies Ltd.

during the welding process. They would, therefore, be an automatic choice for welding Cr-Mo steels and are so used in America and elsewhere, particularly for field welding. With these electrodes pre-heating need not be high, in many cases it may be eliminated, and freedom from weld cracks is assured. The welded joint is, however, in a relatively brittle state, since the Cr-Mo steel will harden to the same extent with any type of electrode. It may be considered to be less brittle than if welded with high tensile Cr-Mo electrodes, since the greater ductility of the austenitic weld metal will tend to absorb strains set up in moving the vessel into the stress relieving furnace.

Thus, at first sight, it would appear logical to select austenitic electrodes for welding Cr-Mo steels, but the problem is likely to be complicated by the fact that the steels are required to operate at high temperatures. The austenitic welds would provide adequate creep resistance and scaling resistance, but the marked difference in coefficient of expansion between austenitic Cr-Ni and ordinary low alloy Cr-Mo weld metal tends to lead to the development of cracks, because on heating and cooling the joint welded with austenitic electrodes is subject to self-generated stresses. In practice the oil refinery equipment using these steels is not generally called upon to stand rapid cyclical changes of temperature, which is the probable explanation of the fact that austenitic electrodes have been used to a considerable extent. Their use is, however, not attractive if others of Cr-Mo type are available and can be shown to provide crack-free joints under properly controlled welding procedures not too elaborate for fabrication shops. In this respect it is assumed that pre-heat temperatures up to 300 deg. C., but preferably not above 150 deg. C., are practicable, and that stress relieving furnaces of suitable size are available for the normal stress relief treatment at 650 deg. C. In other words, elaborate treatments involving full annealing at temperatures of the order of 850 deg. to 950 deg. C. are not to be considered.

Quite apart from the problem of welding without cracking, the question whether the weld has sufficient strength, ductility and scaling resistance at the working temperature must be considered. Also the weld metal should possess a suitable resistance to creep, otherwise premature failure may be expected at this position. Finally, the weld and steel should not be susceptible to embrittlement whether induced by graphite formation or hydrogen. Fortunately the presence of chromium is an insurance against the former, and the 3 per cent. Cr-Mo composition is well known to possess marked resistance to the latter.

To cover the above terms of reference, certain electrodes were selected, including the Cr-Mo and austenitic Cr-Ni types and the pre-heating temperatures suitably restricted. Where doubt arose as to the properties of the weld at high temperatures, mechanical tests were carried out.

The following sections deal with the individual Cr-Mo compositions in the order of ½ per cent. Cr-Mo, 2 per cent. Cr-Mo and 5 per cent. Cr-Mo with a final review of the steels as a group. A short preliminary section describes the crack susceptibility test.

SECTION 2

Crack-Sensitivity, Weld Joint Ductility and Weld Strength. Test Principles and Details

The basic principle of a crack-sensitivity test is to provide exceptionally severe conditions of rigidity at the weld joint. It is preferable that these should be greater than are likely to be met in the welded vessel. To this end test plates of the steel to be examined are chosen of equal thickness to those to be used in the structure, or, if no specific structure is contemplated, thicknesses of ½ in. and 1 in. are convenient sizes to use. The test plates are assembled either to provide fillet welds or butt welds. In both cases they are bolted tightly to a base plate 2½ in. thick, and lateral movement of one plate on the other in the case of fillet welds is prevented by anchor welds on three sides, leaving the fourth side for the actual test weld.

Details of the standard Reeve Fillet Weld Test are well known.

It will be noted that the top plate is 6 in. × 6 in. and the bottom plate 10 in. × 7 in. These plates are made from the steel to be examined. The base plate to which they are bolted is high tensile steel. The anchor welds are usually made with electrodes which are not likely to produce cracked joints; if necessary armour plate welding electrodes may be used. The test weld is, of course, deposited with the electrode which is to be used in the construction of the vessel or, in the case of a general investigation to find suitable electrodes, several tests will be made covering the range of selected electrodes. Close contact between the plates is essential for heat conduction and this is obtained by machining the contacting surfaces.

It has been found that the dimensions of the Reeve test may be altered slightly without interfering to any great extent with its severity. Likewise it may be altered to form a double-ended test to provide two test welds per assembly. Thus, a modification of the standard test which has been used extensively by several investigators employs a top plate 5 in. × 5 in. and a bottom plate 12 in. × 6 in. (Fig. 1). The advantage of this is that the size of ingot generally produced by H.F. furnaces used for experimental work can be

Fig. 1. Reeve test. Modification Z. Pre-heat arrangement.

forged down to give enough material for the modified test but not enough for the standard test. This, however, only holds true up to ½ in. thick slabs. If one desires to test on thicker sections a further modification must be used. In this case the small ingot is forged to square bar of the desired thickness, and this is then incorporated in the assembly in such a manner that the test weld is laid on the bar material, the rest of the top and bottom plate being mild steel. The arrangements are shown in Fig. 2 (a) and 2 (b): in the one case the vertical leg only of the test weld is laid on the bar material and in the other both legs are against the bar.

For simplicity the Reeve test and its modifications will be indicated by letters as follows:

Standard Reeve Test	W
Modified to 5 in. × 5 in. top plate on 12 in. × 6 in. bottom plate double-ended test	X
As X, but modified again to incorporate bar material in top plate only	Y (see Fig. 2 (a))
As X, but modified again to incorporate bar material in top and bottom plates	Z (see Fig. 2 (b))

In order to eliminate incidental pick-up of moisture from the atmosphere, all test electrodes are short circuited for about 30 secs.

Eight s.w.g. and 6 s.w.g. electrodes are used to give welds with ¼ in. and ½ in. leg lengths respectively (single runs).

Three cross sections are sawn from the test weld at approximately 1 in., 2 in. and 3 in. from the start of the weld (Fig. 3).

All three sections are examined microscopically at magnifica-

tions ranging up to ×800 for determination of crack incidence in the weld metal and the heat-affected zone of the plate or bar.

In addition, a hardness exploration with diamond indenter is carried out on the centre section. The majority of the spots are positioned in the zone of maximum hardness so that an average reading can be obtained.

In the case of pre-heated tests the whole assembly, including the base plate, is heated to slightly above the required temperature

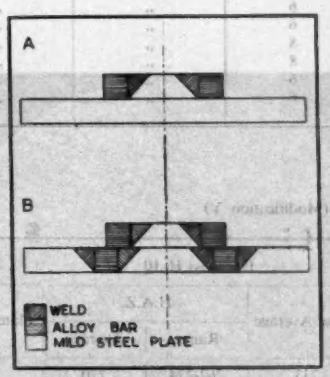

Fig. 1. Modifications Y and Z.

and welding is started when this temperature is reached, as the assembly cools down after removal from the furnace. Temperatures are determined by thermocouple as indicated in Fig. 1.

Experience has shown that it is necessary to allow an incubation period during which the cracks may develop. Therefore, all crack-sensitivity tests are held 18-24 hours in the rigid assembly jig before sectioning.

To determine the strength and ductility of the welded joints it is necessary to use butt welds. Restraint of these welds is achieved by clamping the test plates to a heavy base plate, which simulates the conditions which obtain in constructing large vessels. Since welded vessels in Cr-Mo steels are normally stress relieved before going into service, the butt welds are given 1 hour at 650 deg. C. before being tested mechanically. The strength of the welded joint is indicated by the tensile test, in which fracture may take place in the weld or parent metal. If the latter occurs it is evident that the yield strength of the weld metal is greater than that of the plate but no information as to its ductility is available.

Therefore, it is generally necessary to assess weld metal ductility by bend tests. When welding alloy steels it is not sufficient to test all weld metal specimens, since a pick-up of alloy elements from the plate may affect the weld metal of the structural joint to an appreciable degree. Thus we aim to make a test weld in a similar manner to that to be used in the main structure. The welded joint is then subjected to transverse and longitudinal bend tests. The latter test is generally necessary since it compels the weld metal to contribute its quota of elongation at the outer fibres; in the transverse bend test the bulk of the elongation may be provided by the heat affected zone of the parent plate, if this is lower in yield strength than the weld metal.

Where it is considered advisable the strength and ductility of the welded joint may be determined at the working temperature.

When welding alloy steels the parent plate adjacent to the weld metal which is raised to a high temperature and cooled rapidly may tend to become brittle. In order to assess the ductility of this zone a single bead weld is deposited upon the plate or bar and the weld metal machined off. Bend and Izod impact tests may be carried out in a manner to test the heat affected zone under the bead.

SECTION 3

1 per cent. Cr-Mo Steel

The composition of this steel may be defined by the following ranges of the principal chemical elements:

Carbon	0·10 to 0·15 per cent.
Chromium	0·80 „ 1·10 „
Molybdenum	0·45 „ 0·65 „

It has been used extensively for welded superheater tubes. Knowledge of its behaviour suggested that it would not prove difficult when applied in fabricated vessels. However, it was considered useful to determine the effect of carbon content upon crack susceptibility in a Reeve fillet test and also its influence on heat-affected zone ductility. To provide this information, modified

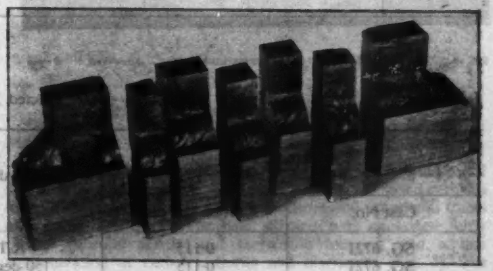

Fig. 3. Method of sectioning Reeve test weld.

Table 1.—Materials

1 per cent. Cr-Mo Steels and 0·5 per cent. Mo Electrodes							Weld Metal Hydrogen. (mls./100 gms.)	
Material	Cast No.	C	Mn	Si	Cr	Mo	Diffusible	Vacuum Extracted
Bar	SG. 6721	0·115	0·44	0·55	0·87	0·52		
Bar	SG. 6801	0·14	0·40	0·63	1·18	0·54		
All weld metal deposit. Commercial 8 s.w.g. electrode		0·055	0·42	—	0·04	0·51	1·8	9·0
All weld metal deposit. Commercial 6 s.w.g. electrode		0·045	0·46	—	0·03	0·52	—	—
Commercial class A.M.S. deposit for comparison		—	—	—	—	—	6·5	8·4
Commercial hydrogen controlled deposit for comparison		—	—	—	—	—	1·1	0·7

Table 2.—Crack Susceptibility in Reeve Test (Modification Y)

Plate Details			Temperature of Test	Electrode S.W.G.	Crack Incidence	
Cast No.	Carbon per cent.	Thickness			Weld Metal	H.A.Z.
SG. 6721	0·115	½ in.	R.T.	8	No cracks	No cracks
SG. 6721	0·115	½ „	150 deg. C.	8	„	„
SG. 6721	0·115	1 „	R.T.	6	„	„
SG. 6721	0·115	1 „	150 deg. C.	6	„	„
SG. 6801	0·14	½ „	R.T.	8	„	„
SG. 6801	0·14	½ „	150 deg. C.	8	„	„
SG. 6801	0·14	1 „	R.T.	6	„	„
SG. 6801	0·14	1 „	150 deg. C.	6	„	„

Table 3.—Hardness Tests. Reeve Test (Modification Y)

Plate			Test Temperature	Hardness H_D10				
Cast No.	Carbon per cent.	Thickness		Weld Range	Metal Average	H.A.Z.		Plate Average
						Range	Average	
SG. 6721	0·115	½ in.	R.T.	228-235	233	262-274	270	227
SG. 6721	0·115	½ „	150 deg. C.	215	215	240-258	250	192
SG. 6721	0·115	1 „	R.T.	240-245	242	283-292	287	164
SG. 6721	0·115	1 „	150 deg. C.	210-224	216	254-262	258	172
SG. 6801	0·14	½ „	R.T.	212-218	214	360-373	366	212
SG. 6801	0·14	½ „	150 deg. C.	212-222	217	330-351	337	205
SG. 6801	0·14	1 „	R.T.	245-254	249	363-397	388	197
SG. 6801	0·14	1 „	150 deg. C.	206-222	215	345-363	352	206

Table 4.—Heat Affected Zone Ductility. Bend Tests

1 in. Square Bar		Weld Bead deposited at	Bend Test. 3 ins. × ½ in. × ½ in. Angle of Bend without Fracture	
Cast No.	Carbon per cent.		Bent at Ro. T.	Bent at 600 deg.-625 deg. C.
SG. 6721	0·115	R.T.	180 deg. C.	160 deg. C.*
SG. 6721	0·115	150 deg. C.	180 deg. C.	160 deg. C.
SG. 6801	0·14	R.T.	180 deg. C.	160 deg. C.
SG. 6801	0·14	150 deg. C.	180 deg. C.	No test result. Defective bar
SG. 6801	0·14	Unwelded	180 deg. C.	160 deg. C.

* Maximum bend angle permitted by the hot bend test jig.

Table 5.—Hardness Tests. Single Bead Welds

Bar		Weld Bead deposited at	Hardness H_D10 As Welded Condition	
Cast No.	Carbon per cent.		Range	Average
SG. 6721	0·115	R.T.	236-242	239
SG. 6721	0·115	150 deg. C.	216-232	225
SG. 6801	0·14	R.T.	289-339	308
SG. 6801	0·14	150 deg. C.	276-294	285

Reeve tests, type Y, were carried out, using a commercial 0·5 per cent. Mo bearing electrode, and the heat-affected zone ductility determined by bend tests on the zone under a single bead weld. The steels were made from 18 lb. H.F. melted ingots forged to bar.

Bar Treatment before Welding.—Heat treated for 1 hour at 760 deg. C. Air cooled.

Reeve Fillet Weld Tests. Y Modification.—The effect of pre-heating to 150 deg. C. and also the effect of plate size were studied by testing at room temperature and at 150 deg. C. and by using $\frac{1}{2}$ in. and 1 in. thick plates.

The results indicate that 1 per cent. Cr-Mo steels may be welded with every confidence in their resistance to hardened zone crack formation. Pre-heating is not required up to 1 in. thickness and no difficulty is imposed if the carbon content of the steel to be used in the particular job is at the top of the making range.

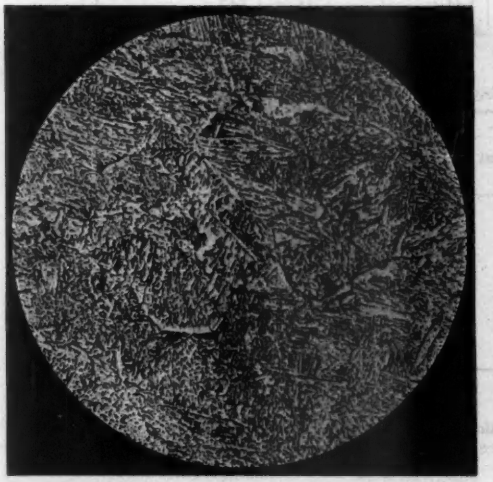

Fig. 4. Weld metal structure, 1 per cent. Cr-Mo plate. 0·5 per cent. Mo electrode. ×300

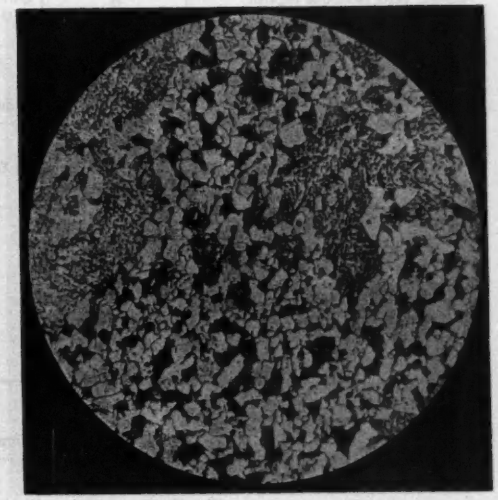

Fig. 6. 1 per cent. Cr-Mo plate structure 1 hour 760°C. A.C. ×300

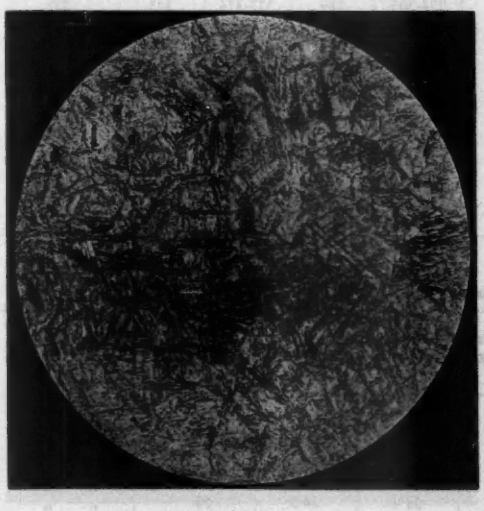

Fig. 5. Heat affected zone structure. As welded. No pre-heat. ×300

Microstructures

In the tests at room temperature the structure of the weld metal was of Widmanstatten type, containing partially dispersed carbides in ferrite with ferrite at the grain boundaries and occasional traces of martensite (Fig. 4). The heat affected zone contained fairly coarse accicular ferrite and martensite merging into a fine agglomeration of carbides, ferrite and martensite (Fig. 5). The parent plate showed dispersed carbides in ferrite with some free ferrite, the carbides tending to be banded (Fig. 6).

Effect of Pre-heating to 150 deg. C. on Microstructures

The weld metals generally showed little or no change, though one weld on the higher carbon plate contained less martensite than the corresponding weld which was not pre-heated.

The heat-affected zone structures in the lower carbon steel were not affected, but those in the higher carbon steel were less accicular, there being a tendency towards more ferrite and carbide and less martensite (Fig. 7).

The essential features of the microstructures are, of course, reflected in the results of hardness tests.

These results show that:

1. Pre-heating to 150 deg. C. tends to reduce the hardness of weld metal very slightly and that of the heat-affected zone by about 30 hardness numbers.
2. Increasing the carbon content of the plate from 0·115 per cent. to 0·14 per cent. increases the hardness of the heat-affected zone by about 100 hardness numbers, but has little or no effect on the weld metal hardness.

Table 6.—Materials

2¼ per cent. Cr. 1 per cent. Mo steels. Cr-Mo and Cr-Ni electrodes								Weld Metal Hydrogen (mls./100 gms.)	
Material	Cast No.	C	Mn	Si	Ni	Cr	Mo	Diffusible	Extracted
7 in. diameter bloom	H7484	0·13	0·44	0·18	—	2·25	1·07		
2½ in. sq. billet	H7488	0·14	0·43	0·14	—	2·27	1·01		
Commercial Cr-Mo electrode deposit	D1	0·08	0·47	—	—	1·09	1·5		
Experimental electrode deposit ..	Murex BP576	0·07	0·74	—	—	2·45	1·53	0·6	2·5
„ „ „ ..	Murex BP559	0·05	0·91	—	—	3·12	0·55	1·6	2·7
Armour plate electrode deposit ..	A	0·07	0·42	—	8·56	21·56	2·98		
„ „ „ „ ..	B	0·09	1·44	—	—	18·44	3·63		

Table 7.—Crack Susceptibility in Reeve Test (Mod. X)

Cast No.	Carbon per cent.	Thickness	Temperature of Test	Crack Incidence		
				Electrode	Weld Metal	H.A.Z.
H7484	0·13	½ in.	R.T.	D1 (8 s.w.g.)	Root crack	100 per cent. crack
			150 deg. C.	„	No cracks	No cracks
			300 deg. C.	„	„	„
			150 deg. C.	BP576 (6 s.w.g.)	„	„
			150 deg. C.	BP559 (6 s.w.g.)	„	„
			300 deg. C.	„	„	„
			R.T.	A	„	„
			150 deg. C.	„	„	„

Table 8.—Hardness Exploration. Reeve Test (Mod. X)

Electrode	Temperature of Test	Test Condition AW=as Welded S=Stress Relieved 1 hr. 650 deg. C.	Hardness H_D10				
			Weld Metal		H.A.Z.		Plate Average
			Range	Average	Range	Average	
D1	R.T.	AW	318-341	329	376-425	398	237
		S	—	309	—	348	229
	150 deg. C.	AW	274-305	289	327-374	355	231
		S	—	294	—	337	221
	300 deg. C.	AW	258-268	265	313-330	322	226
		S	—	289	—	342	210
BP. 576	150 deg. C.	AW	330-345	339	345-363	353	146
		S	—	360	—	341	156
BP.559	150 deg. C.	AW	322-330	326	319-348	331	224
		S	—	327	—	344	217
	300 deg. C.	AW	297-333	323	313-340	327	229
		S	—	327	—	336	212
A	R.T.	AW	215-220	218	348-397	368	224
		S	—	240	—	344	217

Table 9.—Tensile Tests at Room Temperature

Description	Pre-heat Temperature	Yield Stress (tons sq. in.)	Max. Stress (tons sq. in.)	Elongation on 2 ins. (per cent.)	Reduction of Area (per cent.)	Position of Fracture
Unwelded plate	—	15·0	31·9	35·0	45	—
Welded with BP576	150 deg. C.	19·5	32·1	25·0	57	Parent plate
	250 deg. C.	19·9	33·0	24·0	53	„ „
Welded with BP559	150 deg. C.	20·5	32·5	25·0	56	„ „
	250 deg. C.	20·8	32·7	25·0	52	„ „
Welded with electrode B (Cr, Ni, Mo) ..	None	16·0	33·4	24·5	54	„ „

Heat-Affected Zone Ductility

To determine this, a single bead weld was laid on the bar with a 6 s.w.g. commercial hydrogen controlled electrode (to eliminate the risk of cracks). The effect of pre-heating was examined by heating the bar to 150 deg. C., depositing the weld, allowing to cool to room temperature and laying a bead on the opposite side of the bar. After removing the weld metal and superfluous bar material, specimens 3 in.×$\frac{1}{2}$ in.×$\frac{1}{4}$ in. thick were available for bend tests on the heat-affected zones of the pre-heated and unpre-heated welds. The bend tests were carried out at room temperature and at 600 to 625 deg. C.

In view of the apparent anomaly between the very good ductility figures revealed above and the hardness figures in the Reeve tests, it was considered necessary to determine the hardness of the heat-affected zone in the single bead tests.

These results show that the hardness of the heat-affected zone under the single bead welds is slightly lower than that adjacent to the welds in the Reeve tests. This is ascribed to the slower rate

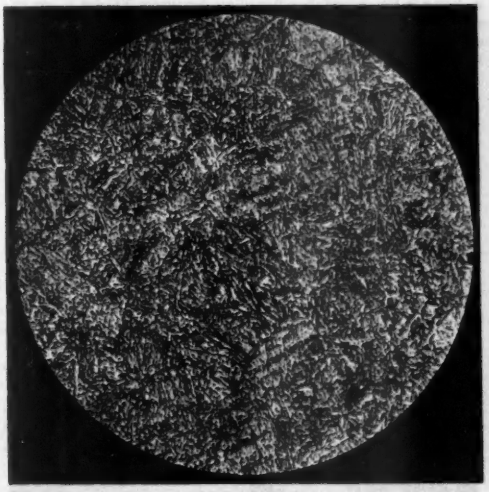

Fig. 7. 14 per cent. C., 1 per cent. Cr-Mo heat affected zone. As welded. Pre-heated 150°C. ×300

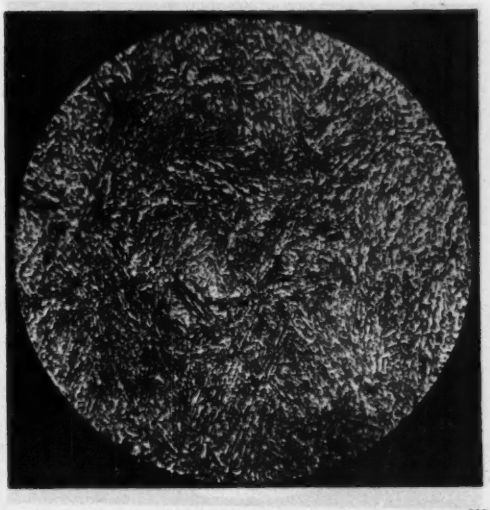

Fig. 9. 1 per cent. Cr-Mo heat affected zone. As welded. Pre-heat 300°C. ×300

Fig. 8. 1 per cent. Cr-Mo heat affected zone. As welded. No pre-heat. ×300

of cooling, which is itself due to the smaller heat sink. The value of these figures lies in the fact that the heat affected zone material, at hardness values of 300 D.P.H., can be bent to 180 deg. without fracture. On this basis a figure of 350 D.P.H. has been taken as the desirable maximum hardness at the weld when the welded vessel is put under load.

Conclusions

1. *Crack Sensitivity.*—One per cent. Cr-Mo steels are not crack sensitive up to ·14 per cent. carbon content and 1 in. thickness.
2. *Electrodes.*—Commercial 0·5 per cent. Mo electrodes can be used.
3. *Carbon Content.*—If the carbon content is at the lower end of the range 0·10 to 0·15 per cent., the welded vessel should not require to be stress relieved. If it is at the top end it would be advisable to stress relieve at 650 deg. C.

SECTION 4

2$\frac{1}{4}$ per cent. Cr, 1 per cent. Mo Steels

These steels may be defined by the following ranges of principal chemical elements:

Carbon	0·15 per cent. maximum
Chromium	2·0 to 2·5 per cent.
Molybdenum	0·90 to 1·10 „

The service temperature of this class of material may be of the order of 600 deg. C., and it is evident that an electrode must be

selected which will have sufficient chromium to prevent a marked difference in rate of scaling of the weld compared with the plate.

Thus the choice is limited to electrodes of the chromium-molybdenum or austenitic chromium-nickel types.

In view of the increased alloy content greater crack sensitivity than was observed with 1 per cent. Cr-Mo steel may be anticipated. This suggests that higher pre-heat temperatures may be required to avoid cracking. The carbon content of the steel must also be regarded as an important factor in crack sensitivity. The following programme of work was carried out:

1. Reeve tests (modification X).
2. Mechanical tests on butt welds.

The influence of the following factors was studied:

1. Electrode type.
2. Pre-heat temperature.
3. Carbon content of the plate.

The main programme of work was carried out on a material from commercial casts of steel, but the effect of carbon content was studied with 18 lb. H.F. melted ingots forged to bar.

Commercial Casts.—Cast H7484 was allocated to Reeve tests, the 5 in. × 5 in. top plates being sawn from the bloom.

Cast H7488 was used for butt weld tests, the plates being forged from the billet.

In all cases the plates were ½-in. thick.

Plate Treatment before Welding.—The Reeve test plates were not treated, the material being in the as-rolled condition. The plates for the butt-welds were heated for 1 hour at 870 deg. C. and air cooled.

Reeve Fillet Weld Tests (Modification X).—The effect of pre-heating at 150 deg. C. and 300 deg. C. and that of electrode composition was studied.

These results show that a pre-heat to 150 deg. C. is sufficient to prevent cracking in the heat-affected zone and weld metal when using Cr-Mo electrodes. Furthermore, increasing the chromium content of the weld metal does not require a corresponding increase in pre-heat temperature to prevent weld metal cracking. It will be noted that pre-heating may be omitted if Cr-Ni armour plate welding rods are used.

Microstructures

The structure of the heat-affected zone in a test without pre-heat is shown in Fig. 8, and the effect of pre-heating at 300 deg. C. on this structure can be judged by comparing Fig. 8 and Fig. 9. The emergence of ferrite and carbide in place of acicular martensite will be noted. The parent plate structure in the as-rolled condition is shown in Fig. 10, and that of the plate after annealing at 870 deg. C., furnace cooled, in Fig. 11.

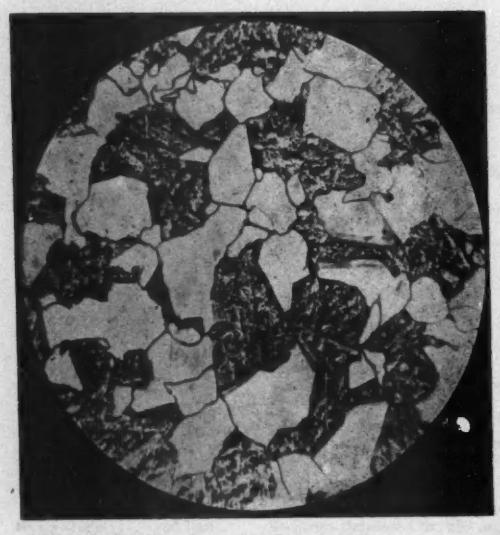

Fig. 10. 2 per cent. Cr-Mo bloom structure. As rolled. × 380

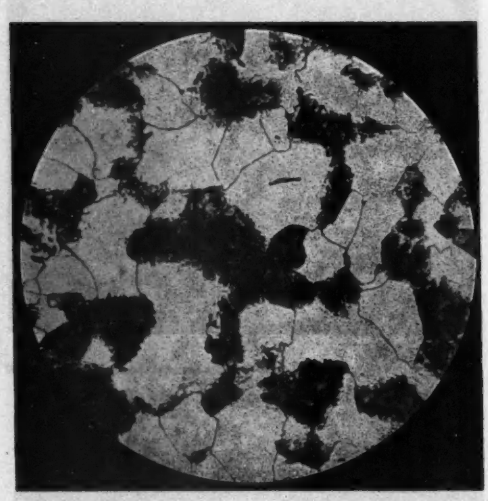

Fig. 11. 1 per cent. Cr-Mo steel. Annealed.

The 3 per cent. Cr-Mo weld metal structure, without pre-heating, can be observed in Fig. 12.

The severity of the cracking which occurs with Cr-Mo electrodes in the absence of pre-heating is illustrated in Fig. 13.

Hardness Exploration

Carried out to act as a guide to the degree of ductility to be anticipated.

These results show that:

1. Pre-heating tends to reduce the hardness of the heat-affected zone, there being a reduction of approximately fifty hardness numbers for a pre-heat of 150 deg. C. and one of about seventy-five numbers for 300 deg. C. pre-heat.

2. It also tends to reduce the hardness of the 1 per cent. Cr-

1½ per cent. Mo weld metal, but has little or no effect upon that from the higher Cr electrodes.

3. Stress relieving at 650 deg. C. has no effect upon the hardness of the 3 per cent. Cr-Mo weld metal (B.P. 559), but tends to increase that of the welds from the 1 per cent. Cr and 2 per cent. Cr electrodes except in the case of the non-pre-heated test. Its effect upon the heat-affected zone is also variable. It reduces the hardness in the case of non-preheated tests, but has little effect upon those that were pre-heated.

4. Increasing the chromium content of the weld metal has little or no effect upon the weld hardness.

5. Stress relieving increases the hardness of the Cr-Ni-Mo weld by precipitation of carbides.

Mechanical Tests on Butt Welds in 2¼ per cent. Cr-1 per cent. Mo Steel, ½-in. plates.—Conditions of fairly severe rigidity were imposed during welding by clamping the plates to a heavy base plate.

Steel Composition.—

	C	Cr	Mo
Cast H. 7488 ..	0·14	2·27	1·01

Condition.—Stress relieved after welding. One hour at 650 deg. C.

It will be noted that fracture occurred in the parent plate in all tests. The only deduction that may be reached is that the yield strength of the weld metals is higher than that of the plate.

Fracture in the temperature tensile tests occurred in the parent plate when welded with the 2 per cent. Cr and 3 per cent. Cr-Mo electrodes so that the superior yield strength of the weld metal is maintained at 610 deg. C.

Welding with austenite armour plate welding rods is not attractive, since one sample failed with low ductility values at the weld metal parent metal junction zone.

The above tensile tests do not give any indication of the ductility of the weld metal itself. To obtain information on this point bend tests were carried out, all specimens being stress relieved at 650 deg. C.

Table 11. Transverse Bend Tests at Room Temperature

Former to Plate Ratio 2 : 1			
Description	Pre-heat deg C.	Angle at 1st Crack	Position of Crack
Welded with B.P.576	150	60 deg.	Heat-affected zone
,, ,, ,,	150	55 ,,	,, ,, ,,
,, ,, ,,	250	65 ,,	,, ,, ,,
Welded with B.P.559	150	106 ,,	At centre of weld and in H.A.Z.
,, ,, ,,	250	90 ,,	,, ,, ,, ,,
,, ,, ,,	250	65 ,,	H.A.Z.
B	None	90 ,,	,,
B	,,	55 ,,	,,

Again the results failed to indicate the weld metal ductility, so that longitudinal bend tests were carried out.

These results in Table 12 suggest that the higher Cr-Mo electrode B.P.559 has slightly better ductility than that containing 2 per cent. Cr-Mo, but the difference is not great.

It is of value to know whether the weld metal is ductile at the working temperature. Therefore, hot bend tests were carried out at 610 deg. C.

Table 10.—Tensile Tests at 610 deg. C.

Description	Pre-heat Temperature	Max. Stress (tons/sq. in.)	Elongation on 2 in. (per cent.)	Reduction of Area (per cent.)	Position of Fracture
Unwelded plate	—	18·5	50	69	—
BP 576	150 deg. C.	20·8	30	63	Parent plate
	150 deg. C.	17·6	34	68	,, ,,
	250 deg. C.	20·8	32	64	,, ,,
BP559	150 deg. C.	20·0	33	68	,, ,,
	250 deg. C.	20·7	32	63	,, ,,
		19·2	33	69	,, ,,
B	None	20·6	13	5·5	Weld junction
	,,	19·8	30	66	Parent plate

Table 12. Longitudinal Bend Tests at Room Temperature

Former to Plate ratio 2 : 1			
Description	Pre-heat deg C.	Angle at 1st Crack	Position of Crack
Welded with B.P.576	250	75 deg. (complete fracture)	Origin probably in the weld metal
B.P.559	250	71 deg.	Weld metal-extending to H.A.Z.
B	None	150 deg.	H.A.Z.

Table 13. Transverse Hot Bend Tests at 610 deg. C.

Former to Plate ratio 1 : 1				
Description	Pre-heat tempera-ture deg. C.	Angle of Bend		Position of Fracture
		A	B	
Unwelded plate	—	180 deg.		—
Welded with B.P.576	150	60 deg.	110 deg.	Weld centre
	250	42 ,,	—	,, ,,
B.P.559	150	168 ,,	87 deg.	,, ,,
	250	110 ,,	—	,, ,,
B	None	38 ,,	66 deg.	A. Junction of weld and plate
				B. Weld Centre

The bend angles at 610 deg. C. appear satisfactory; there is evidently somewhat better ductility in the B.P.559 weld metal. A weakness at the weld metal plate interface is again revealed in the sample welded with austenitic Cr-Ni-Mo electrode B.

It is now possible to summarise the conclusions reached as a

result of the tests on the two commercial 2¼ per cent. Cr-1 per cent. Mo steels.

1. A pre-heat of 150 deg. C. is required to prevent cracks.
2. In the stress relieved condition, butt welds made with 3 per cent. Cr-Mo electrodes show satisfactory mechanical properties.
3. The 3 per cent. Cr-Mo electrode does not present any greater welding difficulties than the 2 per cent. Cr-1 per cent. Mo, and has somewhat better ductility at high temperature.
4. Both Cr-Mo electrodes give weld metal with greater tensile strength than the plate at room and high temperatures.
5. The austenitic armour plate welding electrodes tend to produce joints which lack ductility at the weld metal plate metal interface.

Therefore, taking into consideration the various points raised, it is inferred that 2 per cent. Cr-1 per cent. Mo steels should be pre-heated at least 150 deg. C. and welded with 3 per cent. Cr-0·5 per cent. Mo electrodes.

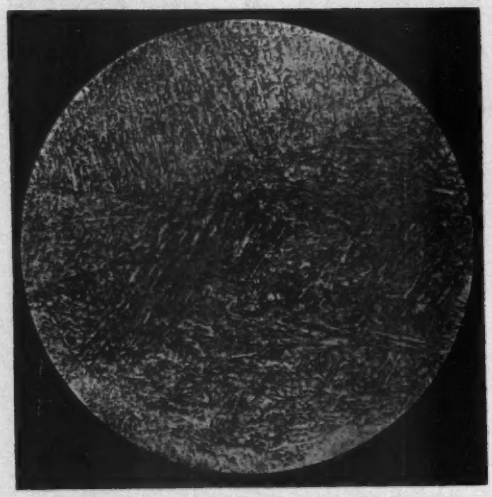

Fig. 12. Weld metal structure. 1 per cent. Cr-Mo plate, 3 per cent. Cr-Mo electrode. As welded. No pre-heat. ×350

The question of carbon content of the plate is a matter which needs examination, since a reduction in carbon content might lead to the elimination of pre-heating.

The effect of carbon content was determined in the same manner as for the 1 per cent. Cr-Mo steels, the factors of pre-heat temperature, of carbon content and plate thickness being studied.

Test Plate Treatment before Welding

All plates were heated 1 hour at 750 deg. C. and air-cooled, before testing. The structure produced by this treatment is illustrated in Fig. 15.

These crack test results are particularly interesting, for it will be noted that welding at room temperature leads to severe weld metal cracking to an extent which so lessens the stress on the heat-affected zone as to prevent cracking therein. This feature is common to the high and lower carbon steels and is independent of plate thickness or electrode composition. It is evident that a pre-heat of 150 deg. C.-200 deg. C. is essential when welding 2¼ per cent.

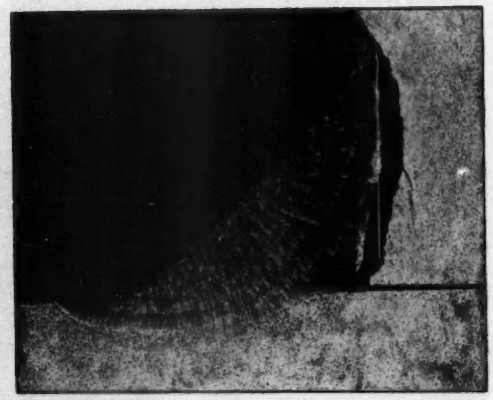

Fig. 13. Severe crack in heat affected zone. 1 per cent. Cr-1 per cent. Mo electrode. As welded. No-pre-heat. ×10

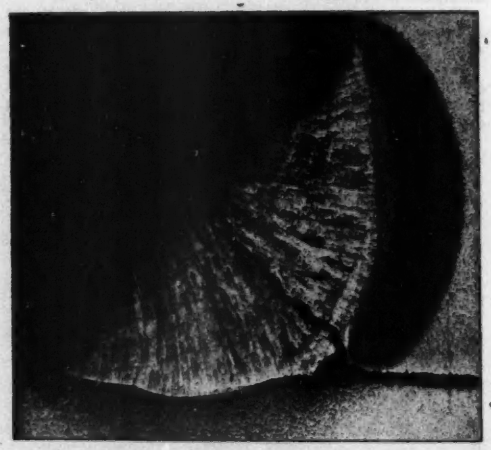

Fig. 14. Typical weld crack in 3 per cent. Cr-Mo weld on 2 per cent. and 5 per cent. Cr-Mo plate. ×10

Table 14. Materials

2¼ per cent. Cr-1 per cent. Mo Steels. Cr-Mo Electrodes

Material	Cast No.	C	Mn	Si	Cr	Mo
Bar	S.G.6723	0·11	0·46	0·38	2·31	1·02
Bar	S.G.6767	0·15	0·50	0·47	2·38	0·98
All weld metal deposit	Murex					
	B.P.576-8 s.w.g.	0·08	1·01	—	2·95	1·95
	6 s.w.g.	0·07	0·99	—	2·6	1·66
	Murex					
	B.P.559-8 s.w.g.	0·07	1·20	—	4·0	0·37
	6 s.w.g.	0·06	1·19	—	3·36	0·43

Cr-1 per cent. Mo steels with Cr-Mo electrodes. A typical weld crack is illustrated in Fig. 14.

These results show that:

1. A carbon content of 0·15 per cent. gives hardness values in the heat-affected zone around 400 H_D 10. Pre-heating to 150 deg. C. reduces this slightly but not to safe values with 1 in. thick plates.

2. Pre-heating has little or no effect upon weld metal hardness.

3. At 0·11 per cent. carbon the hardness level in the heat-affected zone is just above 350 H_D 10 with 150 deg. pre-heat.

Conclusions to be reached from the Tests on 2¼ per cent. Cr-1 per cent. Mo Steels

1. *Pre-heating in Relation to Crack Sensitivity.*—Pre-heating to 150 deg.-200 deg. C. would be expected to prevent cracking in weld or plate irrespective of carbon content.

2. *Pre-heating in Relation to Joint Ductility.*—If the carbon content is 0·10 per cent. or less the pre-heat temperature may be limited to 150 deg. C.-300 deg. C. If it exceeds 0·10 per cent. the pre-heat should be 300 deg. C. to provide reasonable softness in the heat-affected zones.

3. *Electrodes.*—Austenitic Cr-Ni-Mo electrodes are regarded as less desirable than Cr-Mo types due to weld metal-plate metal junction zone weakness. 3 per cent. Cr-0·5 per cent. Mo electrodes are satisfactory.

4. *Stress Relief at 650 deg. C.*—Regarded as very desirable in view of the hardness developed at the joints.

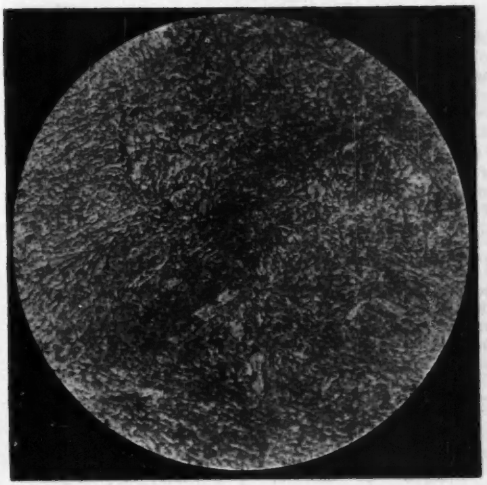

Fig. 15. 5 per cent. Cr-Mo plate hour str ucture. 1760°C. A.C. ×800

Table 15. Crack Susceptibility in Reeve Test (Mod. Y)

Cast No.	Plate Carbon per cent.	Thickness	Temperature of Test	Electrode	Crack Incidence	
					Weld Metal	H.A.Z.
S.G.6723	0·11	½ in.	R.T.	B.P.559 (8)	Marked throat crack extending to surface	No cracks
,,	,,	,,	150 deg. C.	,,	Small root crack	,, ,,
,,	,,	1 in.	R.T.	B.P.559 (6)	Very marked throat crack extending to surface	,, ,,
,,	,,	,,	150 deg. C.	,,	No cracks	,, ,,
S.G.6767	0·15	½ in.	R.T.	B.P.559 (8)	Marked throat crack	,, ,,
,,	,,	,,	150 deg. C.	,,	No cracks	,, ,,
,,	,,	1 in.	R.T.	B.P.576 (6)	Very marked throat crack extending to surface. Numerous small cracks	,, ,,
,,	,,	,,	150 deg. C.	,,	No cracks in two sections. Small root crack in one	,, ,,

Table 16. Hardness Exploration. Reeve Test (Mod. Y)

Cast No.	Plate Carbon per cent.	Thickness	Temperature of Test	Electrode	Hardness H_D10				
					Weld Metal		H.A.Z.		Plate Average
					Range	Average	Range	Average	
6723	0·11	½ in.	R.T.	B.P.559	383-387	386	383-397	388	187
6723	0·11	,,	150 deg. C.	,,	363-376	372	351-357	354	179
6723	0·11	1 in.	R.T.	,,	345-360	353	383-401	393	197
6723	0·11	,,	150 deg. C.	,,	348-366	358	366-373	370	189
6767	0·15	½ in.	R.T.	,,	366-383	375	390-409	403	192
6767	0·15	,,	150 deg. C.	,,	380-383	382	380-387	383	213
6767	0·15	1 in.	R.T.	B.P.576	373-380	375	397-425	415	206
6767	0·15	,,	150 deg. C.	,,	348-360	356	380-401	395	189

SECTION 5

5 per cent. Cr-Mo Steels

The composition of this steel may be defined by the following ranges of principal chemical elements:—

Carbon	0·12 per cent. maximum
Chromium	4·5 to 5·5 per cent.
Molybdenum	0·45 „ 0·65 „

Owing to the relatively high alloy contact a considerable measure of hardening may be expected when arc welding. The hardening intensity depends upon carbon content, since with the above chromium content martensitic structures are bound to be formed adjacent to the weld deposit.

Therefore, carbon may be regarded as the most important factor in the weldability of this type of steel, and an investigation into the effect of this element on crack sensitivity and the extent to which its harmful effects could be reduced by pre-heating was carried out. Only one type of electrode was used, namely, 3 per cent. Cr-Mo.

Table 17. Materials

5 per cent. Cr-0·5 per cent. Mo Steels. 3 per cent. Cr-Mo Electrodes

Material	Cast No.	C	Mn	Si	Cr	Mo
Bar	S.G.6725	0·12	0·43	0·34	5·15	0·52
„	S.G.6724	0·16	0·45	0·38	5·30	0·53
„	S.G.6826	0·09	0·40	0·35	5·08	0·55
„	S.G.6828	0·10	0·42	0·37	5·20	0·55
„	S.G.6829	0·16	0·45	0·37	5·20	0·55
„	S.G.6827	0·17	0·37	0·33	5·14	0·55
All weld metal deposit	Murex					
	B.P.559 ⅛ s.w.g.	0·07	1·20	—	4·0	0·37
	6 s.w.g.	0·06	1·19	—	3·36	0·43

Plate Treatment before Welding.—1 hour 760 deg. C., air cooled.

Electrodes.—All tests were welded with B.P.559 electrodes.

Crack Sensitivity.—Reeve tests (mod. Y) were carried out on S.G.6725 and S.G.6724, to determine the effect of pre-heating to 150 deg. C.

It is apparent from these results that pre-heating to 150 deg. C. is insufficient to prevent heat-affected zone cracking in ½ in. as well as 1 in. thick plates. (It will be recalled that 150 deg. C. pre-heat was sufficient for this purpose with the 2¼ per cent. Cr-Mo steel up to 0·13 per cent. carbon content.)

Microstructures

The weld metal structures were similar to those observed when welding 2¼ per cent. Cr-Mo steels; mixed structures of martensitic appearance with ferrite and carbide. The pre-heating at 150 deg. C. had no effect upon these structures. The heat-affected zone contained mainly accicular martensite with some granular carbide merging into a fine dense agglomeration of carbides, martensite and ferrite. Again the pre-heating had no effect. The parent plate structure is shown in Fig. 15. The fine crack in the heat-affected zone of the 1 in., 0·16 per cent. C, 150 deg. C. pre-heat sample is illustrated in Fig. 16.

The hardness values in the H.A.Z. column of Table 19 confirm the cracking test results; pre-heating to 150 deg. C. has no effect on the structures developed in the heat-affected zone and this applies to 0·12 per cent. carbon as well as 0·16 per cent. carbon steels.

Tests were therefore carried out on lower carbon steels and on high carbon steels (0·16 per cent. C) to determine the effect of lower carbon content and higher pre-heat temperatures.

Fig. 16. Fine crack in heat affected zone. Pre-heated to 150°C., 0·16 per cent. C., 5 per cent. Cr-Mo steel. ×30

The results in Table 20 suggest that pre-heating to 250 deg. C. eliminates cracking in the weld and heat-affected zone with carbon contents up to 0·16 per cent. For low carbon contents of the order of 0·10 per cent. a pre-heat of 200 deg. C. is apparently satisfactory.

Comparing Tables 21 and 20, it would appear that pre-heating to 250 deg. C. eliminates cracking from the 0·17 per cent. carbon

Table 18. Crack Susceptibility in Reeve Test (Mod. Y)

Cast No.	Plate Carbon per cent.	Thickness	Temperature of Test	Electrode s.w.g.	Crack Incidence	
					Weld Metal	H.A.Z.
6725	0·12	½ in.	R.T.	8	Marked root crack	No cracks
6725	0·12	„	150 deg. C.	8	No cracks	Cracks in Sections 2 and 3
6725	0·12	1 in.	R.T.	6	Very marked crack reaching the surface	No cracks
6725	0·12	„	150 deg. C.	6	No cracks	Cracks in all sections
6724	0·16	½ in.	R.T.	8	Marked cracking	No cracks
6724	0·16	„	150 deg. C.	8	Small root cracks	No cracks
6724	0·16	1 in.	R.T.	6	Numerous small intergranular cracks	Small crack in all sections
6724	0·16	„	150 deg. C.	6	No cracks	Small fine crack in all sections

steels. Nevertheless, the hardness in the heat-affected zone tends to exceed 400 D.P.H., which must be regarded as unsatisfactory from the point of view of ductility. The low carbon steels 6828 and 6826, on the other hand, do not quite reach 400 D.P.H., which emphasises the value of low carbon content as opposed to pre-heating, which has little or no effect upon the heat-affected zone hardness.

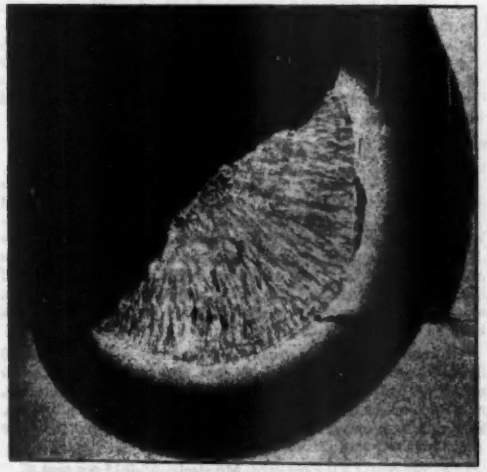

Fig. 17. Sound weld in 0·17 per cent. C., 5 per cent. Cr-Mo steel. Pre-heat 250° C., 5 per cent. Cr-Mo electrodes. ×7

Thus the welding procedure must, to some considerable extent, be decided by the particular job: on the one hand it is evident that a pre-heat to 250 deg. C. is quite sufficient to prevent cracking in the joint, even with a carbon content considerably higher than the limit in the specification. This is illustrated in Fig. 17. For some applications this may be sufficient to enable the welded component to be moved to the stress relieving furnace in spite of the presence of hard zones near the weld.

On the other hand, when there would appear to be risk of cracks being produced in the hard zones by handling after welding, the procedure must be set out to prevent the formation of substantial areas of martensite near the welds. This can be done in two ways:

(*a*) By reducing the carbon content to 0·08 per cent. maximum,

or (*b*) By not allowing martensite to form. This can be accomplished by pre-heating to somewhat above 300 deg. C., maintaining this temperature during the entire welding process and, without allowing to cool below 300 deg. C., applying full annealing or stress relieving.

The second alternative is difficult to apply in practice to anything in the nature of a large vessel. Thus the value of low carbon content in promoting the use of Cr-Mo steels is evident.

A further possibility is to use a 5 per cent. Cr-Mo steel treated with titanium. Although this gives a measure of control over crack sensitivity and heat-affected zone hardness, there is some evidence that a different form of brittleness is introduced in the heat-affected zone. Thus further work on the titanium treated steels requires to be carried out before they can be regarded as a solution comparable with that of low carbon content.

Table 19. Hardness Exploration Reeve Tests (Mod. Y)

Cast No.	Plate Carbon per cent.	Thickness	Temperature of Test	Hardness H_D10				
				Weld Metal		H.A.Z.		Plate Average
				Range	Average	Range	Average	
6725	0·12	½ in.	R.T.	394-397	395	421-437	426	233
6725	0·12	,,	150 deg. C.	390 (3)	390	405-417	411	219
6725	0·12	1 in.	R.T.	357-378	377	413-429	421	213
6725	0·12	,,	150 deg. C.	348-366	358	366-373	370	218
6724	0·16	½ in.	R.T.	366-387	380	429-437	432	240
6724	0·16	,,	150 deg. C.	397-409	402	421-437	429	227
6724	0·16	1 in.	R.T.	366-376	372	421-429	427	227
6724	0·16	,,	150 deg. C.	363-380	374	421-442	428	228

Table 20. Crack Susceptibility Reeve Tests (Mod. Z)

Cast No.	Plate Carbon per cent.	Thickness	Temperature of Test. Deg. C.	Electrode s.w.g.	Crack Incidence	
					Weld Metal	H.A.Z.
6828	0·10	½ in.	200	8	No cracks	No cracks
6828	0·10	,,	250	8	,, ,,	,, ,,
6826	0·09	1 in.	200	6	,, ,,	,, ,,
6826	0·09	,,	250	6	,, ,,	,, ,,
6829	0·16	½ in.	200	8	,, ,,	Small crack in Sections 2 and 3
6829	0·16	,,	250	8	,, ,,	No cracks
6827	0·17	1 in.	200	6	,, ,,	,, ,,
6827	0·17	,,	250	6	,, ,,	,, ,,

SECTION 6

SUMMARY AND DISCUSSION OF RESULTS

Summary

The problem of welding chromium-molybdenum steels in plate form has been considered from the point of view that, in the first place, the welded joint must be made in a manner to avoid cracking during or shortly after the welding operation and secondly that there shall be sufficient ductility in the joint to preclude the possibility of cracks developing when the structure is loaded.

In order to provide for the first of these requirements the Reeve fillet weld test was used and welding factors adjusted until freedom from cracking was obtained. The second requirement was fulfilled by selecting a hardness of 350 D.P.H. as being the maximum value which should be permitted in the fabricated structure as it goes into service.

Three types of chromium molybdenum steel were examined and the welding procedures necessary to give effect to the above requirements were determined.

1 per cent. Cr-0·5 per cent. Mo. Carbon 0·15 per cent. maximum

These steels may be welded without cracking with commercial 0·5 per cent. Mo. electrodes in plate thickness up to 1 in. without special welding procedures. At the higher carbon levels and in the thicker sizes (*e.g.* 0·14 per cent. C and 1 in. respectively) it is desirable that the plates be pre-heated to 150 deg. C. to meet the requirement of 350 H_D 10 maximum.

Stress relief treatment at 650 deg. C. is regarded as desirable in the case of thick plates and carbon contents at the top of the range.

2¼ per cent. Cr-1 per cent. Mo. Carbon 0·15 per cent. maximum

A pre-heat of 150 deg. C.-200 deg. C. is regarded as essential to avoid cracking. The steels may be welded with 3 per cent. Cr-Mo electrodes, which are preferred to 18 Cr- 8 Ni-Mo electrodes.

To ensure the hardness does not exceed 350 D.P.H. the steels can be divided into two groups.

(*a*) Those with carbon contents exceeding 0·10 per cent.

(*b*) Those with carbon contents at or less than 0·10 per cent.

The welding procedure for the former requires a 300 deg. C. pre-heat, whereas for the latter group the pre-heat range could be reduced to 150 deg.-200 deg. C.

Stress relief at 650 deg. C., though it does not reduce the hardness levels appreciably, is considered very desirable to eliminate the internally stressed state which must exist in the as-welded condition in these steels.

5 per cent. Cr-0·5 per cent. Mo. Carbon 0·12 per cent. maximum

Cracking may be prevented by pre-heating to 200 deg. C. if the carbon content does not exceed 0·10 per cent., and to 250 deg. C. if it exceeds this value.

As regards ductility at the joint, pre-heating has little or no effect on the ultimate hardness of the heat-affected zone, which is controlled by carbon content. To obtain values less than 350 H_D10 the carbon content should not exceed 0·08 per cent. The only alternative would appear to be a heat treatment cycle designed to prevent the formation of martensite, which is unlikely to appeal to fabricators.

Discussion of the Results

Several interesting features have been noted in the course of this study of the weldability of Cr-Mo steels. In the first place weld-joint cracking with Cr-Mo electrodes, whether in the weld metal or heat-affected zone, is eliminated by pre-heating to 150 deg.-200 deg. or 200 deg.-250 deg. according to composition. This is effective despite the presence of martensitic structures in the heat-affected zones of the 2 per cent. Cr and 5 per cent. Cr-Mo steels. It is, therefore, comparatively easy to weld these steels with Cr-Mo electrodes without cracking.

However, to restrict the maximum hardness in the joint to 350 D.P.H. is, in the case of the 2 per cent. Cr and 5 per cent. Cr-Mo steels, relatively difficult. The most satisfactory way, that is to say, that which reduces the difficulties of the fabricator to a minimum, is to aim at a low carbon content in the steel. On this basis the preferred maximum carbon contents would be:

1	per cent.	Cr	0·5	per cent.	Mo	steel	..	0·15 per cent.	C
2¼	„	„	1·0	„	„	„	..	0·10 „	C
5	„	„	0·5	„	„	„	..	0·08 „	C

Acknowledgments

The author wishes to acknowledge his debt to his colleagues, in particular Mr. M. Birkhead, in the welding, metallurgical and chemical sections of the Research and Development Department, Stocksbridge, for their part in the work carried out.

He also thanks Mr. G. R. Bolsover, Director and Chief Metallurgist of Messrs. Samuel Fox & Co. Ltd., Stocksbridge, for supplying the commercial steels, and Mr. A. Davies, of that firm, for help in preparing the tests.

Finally, he wishes to thank Mr. F. H. Saniter, Director of Research, and the Directors of The United Steel Companies Ltd., for permission to publish the results.

Table 21. Hardness Exploration Reeve Tests (Mod. Z)

Cast No.	Plate Carbon per cent.	Thickness	Temperature of Test. Deg. C.	Hardness H_D10				
				Weld Metal		H.A.Z.		Plate Average
				Range	Average	Range	Average	
6828	0·10	½ in.	200	363-376	370	380-397	388	210
6828	0·10	„	250	354-380	368	376-387	382	207
6826	0·09	1 in.	200	348-360	353	387-397	391	205
6826	0·09	„	250	339-357	352	366-394	380	206
6829	0·16	½ in.	200	373-383	378	433-446	440	227
6829	0·16	„	250	380-383	382	419-442	428	219
6827	0·17	1 in.	200	370-390	380	437-450	446	213
6827	0·17	„	250	354-366	362	387-397	391	205

ASPECTS OF WELDING DISTORTION IN SHIPBUILDING

By D. M. KERR

This paper, read to the Dundee and Hull Sections of the Institute last February and March, formulates a number of propositions as to the methods of preventing distortion in ship welding, based upon tests conducted by the author, the results of which are described. The methods are analysed and tabulated.

WELDING has established itself as a satisfactory method of joining metal components in ships structures.

Compared with riveting its use obtains an appreciable reduction in steel used, considerable scope and simplicity in design, and superior efficiency in service conditions. Yet welding development has not proceeded at a rate consistent with the economies offered by its use.

One deficiency in the use of welding, despite the potential economies available, is the sequence of serious and costly problems arising in the form of distortion and shrinkage, particularly in enamelled casings and bulkheads in ships' accommodation and painted superstructures.

Here the Shipbuilders' good reputation can be seriously damaged by distorted steelwork showing hideously under accommodation lighting inside and sunlight outside the ship.

Methods of rectifying distortion in welded steelwork are known and effective, but are costly. The problem of eliminating welding distortion is to do it economically.

Management Policy Related to Methods of Eliminating Distortion

The problem should first be tackled in ship design, but the designer's scope is likely to be limited because he usually has not the experience of the shop or yard personnel in meeting the everyday problems of welding distortion. It is necessary for the designer to obtain information from those intimate with the practice of fabricating, assembly, fairing and welding, and to apply it to design.

The transmission of information from the job level to the design department in itself requires careful control by a responsible official, because too often the design department is not fully advised of all necessary facts, and may produce remedies worse than the disease. Each particular job requires treating as a specific problem and corrective methods should be applied to suit that problem. By this procedure, reliable and economical methods may be evolved and used as standard practices. With this objective in view the salient points of this paper describe certain investigations carried out in the author's works for the purpose of giving guidance to the design department and setting up particular codes of practice in the shops and building berths.

Fundamentals in Welding Distortion

The phenomenon of expansion and contraction of steel due to heating and cooling is well known in most forms of metal working and treatment.

Changes in size of the steel affected by heating and cooling are accompanied by a measurable stress, if the steel is restrained from movement. Cases of uniaxial stresses, which may be considered simple stress systems, may be readily expressed by Hooke's Law. But change of size is triaxial, resulting in complex stress systems, requiring higher mathematics to express them.

In arc welding the plate areas are cold at the initial striking of the arc, and as welding proceeds, heat from the welding area is dissipated through the plate, which tends to expand. At the same time the molten weld freezes and tends to contract as welding proceeds.

Expansion and contraction therefore occur at the same time, and if confined to those components only, produce a complex stress system; but increase of welding complicates this further, producing probably an indeterminate stress system.

The elementary principles involved are illustrated as follows in Rollason's *Metallurgy for Engineers* (pp. 49-50):—

"If molten metal is poured from a ladle into a mould and allowed to solidify it is found that the solid metal does not

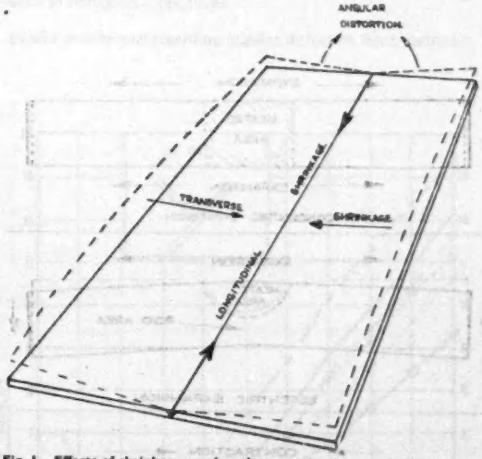

Fig. 1. Effects of shrinkage causing plate to take shape as in dotted lines

completely fill the mould. This shrinkage of metal in the mould is made up of three parts:

1. Contraction in the liquid state between casting and freezing temperatures.
2. Shrinkage owing to solidification.
3. Contraction in the solidification.

Typical values of contraction are:

Percentage of Volume at 20 deg. C. Steel	
Liquid contraction per 100 deg. C.	0·80
Freezing contraction	3·00
Solid contraction	7·35

Thus, according to Rollason, a volumetric contraction of

10·35 per cent. at least occurs in the cooling of the weld zone in mild steel.

In cooling to its freezing point (1500 deg. C. approx.) the liquid metal takes the shape of the solid metal surrounding the molten pool, and it itself causes no appreciable stress.

At 1500 deg. C. the liquid metal solidifies but is highly plastic. This state decreases with temperature and is accompanied by a progressive increase in strength until 900 deg. C. approx. is reached. During this phase contraction occurs and causes appreciable stresses in the surrounding metal.

Should the surrounding metal be so rigid as not to deform under the stress initiated from the heated weld metal, the weld metal itself will undergo hot working and will change its shape according to the restraint imposed on it. But a state of absolute rigidity in the surrounding metal is most improbable, so that deformation in these areas is almost certain to occur.

As the temperature falls below 900 deg. C. the plastic state is considerably reduced. The contracting weld metal now exerts high stresses within itself and in the surrounding metal. In this condition measurable deformation of the joint is almost certain and in practice is known as distortion.

Eccentricity of Thermal Disturbance in Welded Joints

For practical purposes distortion may be considered to occur as longitudinal and transverse shrinkage, and angular distortion (Fig. 1).

Angular distortion is the tendency for the plate to rotate about the longitudinal axis of the joint and is the result of transverse shrinkage being eccentric to the neutral longitudinal axis of the deposited weld metal (Fig. 2).

If it were possible to produce metal arc welds absolutely concentric to the neutral longitudinal axis, theoretically, angular distortion would not occur. In practice, however, eccentricity of heated metal invariably exists to a certain degree in any joint being welded.

The nearest approach to concentricity of a heated welded joint may be found in the "flash butt welding" process. Here the rate of heat conduction is practically uniform from all points parallel to the weld zone. Therefore expansion and contraction occur uniformly.

Fig. 3. Square butt weld made in one run penetration complete to underside. Molten weld metal supported by refractory backing bar. Contraction is concentric.

In arc welding, the nearest approach to concentricity is obtained by welding the joint completely in one run, using a grooved refractory backing-bar to support the run on the underside (Fig. 3).

In this case there will be relatively uniform heating and shrinkage

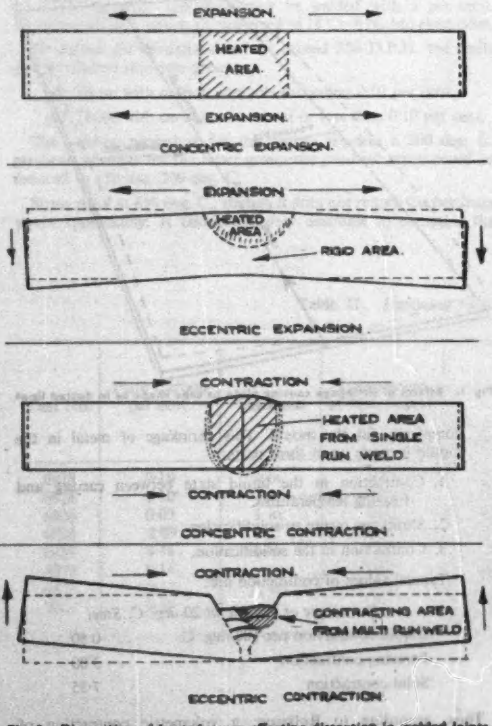

Fig. 2. Disposition of heated zones effecting distortion in welded joints.

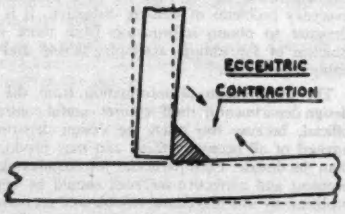

Fig. 4. Contraction from single run fillet.

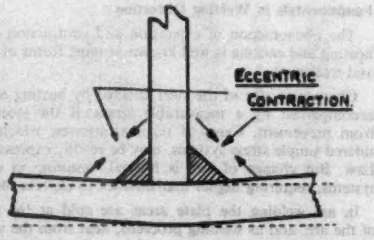

Fig. 4a. Contraction from double run fillet.

on opposite sides of the neutral axis of the weld, something similar to the effects of flash butt welding.

In fillet welds the condition is different. Here the form of joint does not permit concentricity of the weld about the longitudinal neutral axis of the joint, as in the butt weld. Therefore in the fillet welded joint the distortion problem is permanent (Fig. 4).

Because of this tests were carried out at the author's works to ascertain the extent of angular distortion likely to be obtained in fillet welds from particular welding procedures.

The hypothesis was—"The plate members would rotate about a common axis to a constant degree for each run of metal deposited, irrespective of size of rod used."

The tests comprised six ½-in. plate tee fillets fitted into the jig shown in Fig. 5. The pointers welded to each limb of the joint

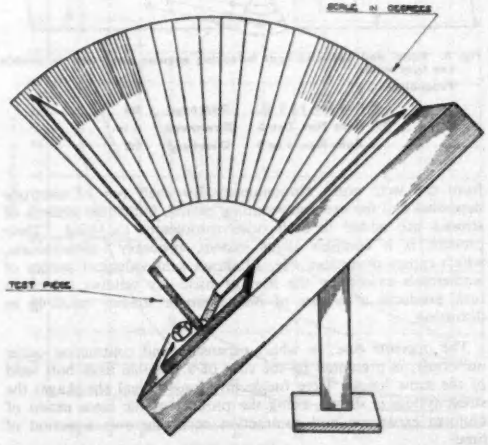

Fig. 5. Test piece and jig for recording angular distortion in filler welds.

indicated on the scale the extent of angular distortion obtained from each run deposited.

The test results are plotted in Fig. 6. In this case the angular distortion for each test of 10 runs results in an average of 11·3 degrees or 1·13 degrees per run deposited. From this two considerations are submitted:—

(*a*) "Angular distortion in fillet welds is the product of the number of runs deposited, and is equal for an equal number of runs, irrespective of size of rod used."

(*b*) "Angular distortion in fillet welds is the lowest when the weld is made in one run."

Similar tests for angular distortion were carried out on 60 degrees VEE welds, using the same jig. The results are plotted in Fig. 7.

It is interesting to note that the first run obtains the lowest degree of angular distortion throughout the weld, and as the Vee is filled with weld metal, the joint appears to increase restraint against angular distortion after the fifth run.

The effect of the first run is similar to that of the square butt weld made in one run, *i.e.* angular distortion is reduced to the lowest practicable limits.

To test this theory, tests were made in six square butt welds by hand, deep penetration electrodes being used. The results showed an average of 1·09 deg. distortion.

From the above considerations it may be assumed that to reduce angular distortion in butt welds it is best to make the weld using a well-formed reinforcement of weld penetration on the opposite side of the joint and to complete it in one pass of the arc. Practical difficulties arise in plates over ¾ in. thick, due to electrode limitations. Here it is necessary to resort to single and double Vee edge preparation for thicker plates. In these cases the possibility of eccentricity of weld metal about the neutral axis is most likely to occur.

It has been found that by equalising the numbers of runs used on each side of the butt a fairly effective control of angular distortion may be maintained. A typical case is cited in Fig. 8. Here a 1½ ins. thick plate butt was welded at the berth with 4 runs of ¼-in. electrode in the downhand position and 4 runs of 8G. in the overhead position, the joint having a flat surface after welding.

Observations on long welds of 1½ in. thick engine bedplates, having a double Vee preparation, and welded by 2 runs each side by automatic welding machines confirmed this theory.

Consequently the following proposition is submitted:—

> "In double Vee butts where the number of runs is equal on opposite sides of the joint, irrespective of electrode size within practical limits, angular distortion will be reduced to a minimum."

It must be mentioned that this procedure does not eliminate buckling caused by longitudinal shrinkage in long joints, though it tends to reduce its proportions.

Similar conclusions regarding angular distortion from particular

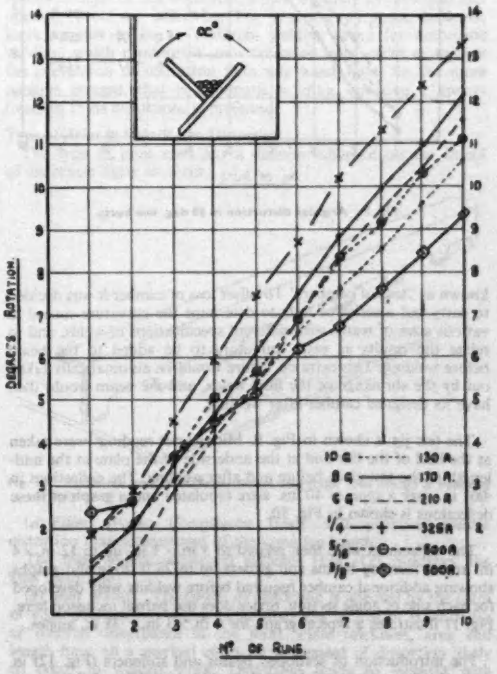

Fig. 6. Angular distortion in filler welds.

welding procedures have already been established by W. Heigh (*Practice of Arc Welding*, pp. 95-97).

Eccentricity of Welds in Beams, Girders and Similar Scantlings

Welded design in shipbuilding has introduced a satisfactory method of incorporating the strength of the channel section by the use of the toe on welded angle or flanged plate. Where the toe is continuous there is a tendency for the longitudinal shrinkage of the fillet welds to cause permanent deflection in the beam,

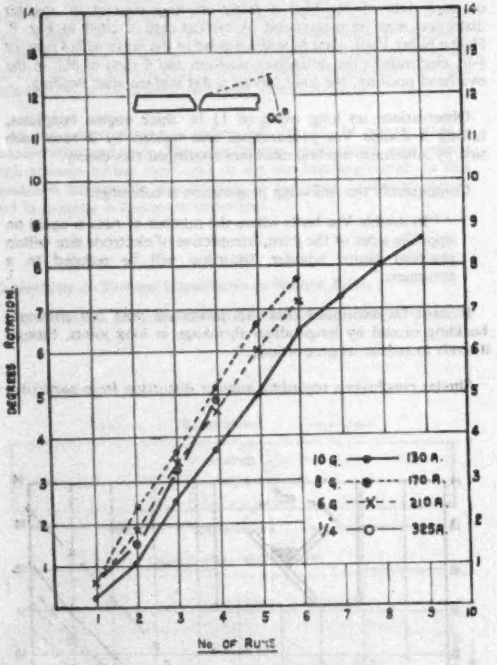

Fig. 7. Angular distortion in 60 deg. vee butts.

known as "loss of camber." To offset loss of camber it was decided to carry out a series of tests to determine the curvature caused in various sizes of seams with different specifications of welds, and to relate the results as extra curvature to be added to the beam before welding. This extra curvature would be automatically taken out by the shrinkage of the fillet welds, and the beam would then have its designed camber after welding.

The test jig is shown in Fig. 9. Micrometer readings were taken at the heel of the bar and at the underside of the plate at the mid-length of the test piece before and after welding. The deflections in ·001 in. over a span of 40 ins. were tabulated and a graph of these deflections is shown in Fig. 10.

The deflections were then related to 3 in. ×3 in. up to 12 in. ×4 in. angles forming beams and girders up to 28 ft. long and graphs showing additional camber required before welding were developed for each side of angle section. Space does not permit inclusion here. Fig. 11 illustrates a typical graph for 6 in. ×3 in. ×·38 in. angles.

The introduction of scalloped beams and stiffeners (Fig. 12) in the author's works has reduced the extent of welding deflection to negligible proportions. The necessity to pre-camber to offset welding deflection does not arise.

Speed and Continuity of Welds. Effects on Distortion in Butt and Seam Welds

When welding a butt a complex system of stresses is set up by varying expansion and contraction rates occurring in the plate members at the same time. If the case were a butt weld requiring one run length of electrode only, the stress system would be relatively simple. But in hand welding, during the change of electrode, contraction occurs in the cooling areas, and expansion in the areas which are being heated up as heat dissipates itself away

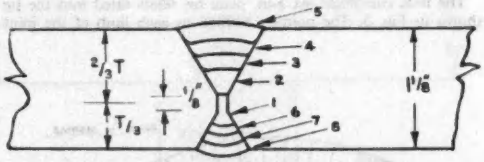

Fig. 8. Equal and opposite runs balancing angular distortion in double vee butt welds.

Procedure:—

Run No. 1	Overhead	8G
Runs Nos. 2 to 5	Downhand	¼ in.
Runs Nos. 6 to 8	Overhead	8G

from the weld zone. Consequently for each run of electrode deposited and for each non-welding period, individual systems of stresses are added to each other throughout the joint. Their product is a complex stress system, probably indeterminate, which causes distortion. Fig. 13 shows a hypothetical system of isothermals caused by the heat of hand arc welding, which in turn produces a system of indeterminate stresses resulting in distortion.

The opposite case, in which expansion and contraction occur uniformly, is presented by the case of a possible flash butt weld of the same length. Here (neglecting longitudinal shrinkage) the stress system is simple, being the product of the same extent of uniform expansion and contraction occurring over a period of time.

Flash butt welding of ships' plating has not yet developed to such an extent but should do so in the future. The industry, however, can use the nearest approach, which is afforded by automatic welding machines, having high welding speeds and weld penetration

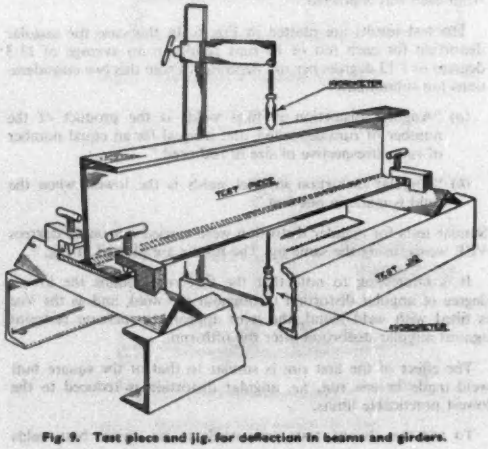

Fig. 9. Test piece and jig for deflection in beams and girders.

possibilities, and able to weld in one pass up to ¼ in. thick plate at speeds of from 25 in. to 30 in. or more a minute. In stressing this particular point the following theory is submitted:—

"It is considered that there is a welding speed for every thickness when the rate of dissipation of heat from the line of weld will be such that the total expansion at any given points will be equal, thus maintaining equilibrium of expansion stresses throughout the weld and plating."

An attempt to illustrate this theory is made in Fig. 14. which shows a butt to be machine welded along the centre joint of

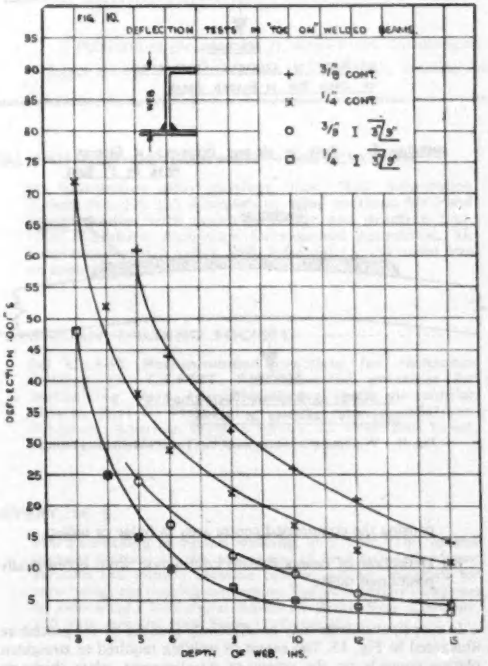

Fig. 10

two plates. The plates are marked off into areas A-A′, B-B′, and so on up to R-R′, by ordinates transverse to the centre line of the weld and plate edges X-X and X′X′.

It is proposed to consider the effect of expansion from welding on each area, as if it were an independent unit free from influence of the other areas. If the entire joint is welded at a speed faster than the rate of thermal conductivity away from the weld, then heat diffusion may still be proceeding from the weld in area A-A′ by the time area R-R′ is completed. In such a case the entire plates would be subject to a general and progressive condition of expansion before cooling and contraction occurred in the area at the start of the weld. Therefore, if there are no appreciable opposing expansion and contraction stresses set up in the plates at the same time, it is reasonable to assume that considerably less distortion is likely to occur than when a similar joint is welded by hand because the intermittent heating and cooling accompanying any hand welding process are certain to develop opposing stresses.

The theory is now taken a step further. Assume that it is practicable to machine weld at such a speed that the rate of thermal conductivity produces equal overall expansion in each area A-A′ to R-R′. Then the temperature gradient and area heating within each area, although both variables, if equated, may produce a constant. If this is true, then expansion from the line of weld to the plate edges X-X and X-X′ would be equal throughout the length of the plate. It is agreed that cooling and contraction would not follow in the same precise order, because of the time lapse between starting and finishing the weld; but they would be of a more uniform condition than where appreciable cooling stresses are already established in a joint still in the process of welding.

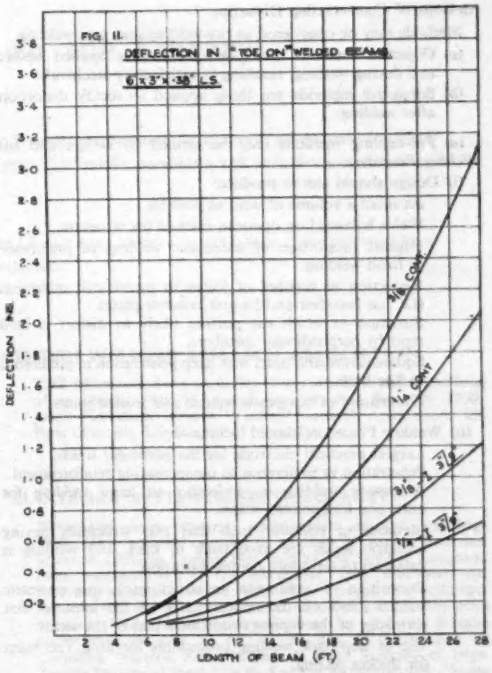

Fig. 11

The author has no data other than observation of practical results to support this argument, which is purely hypothetical and open to proof or otherwise. For practical purposes, however, there appears to be an optimum welding speed for automatic welding, which produces a joint far more satisfactory as regards the prevention of distortion than any hand weld. So the more positive process, that is automatic welding, ensuring a greater freedom from distortion, is preferred.

Type of Joint in Relation to Distortion

The type of joint used has a definite influence on the extent of distortion likely to occur.

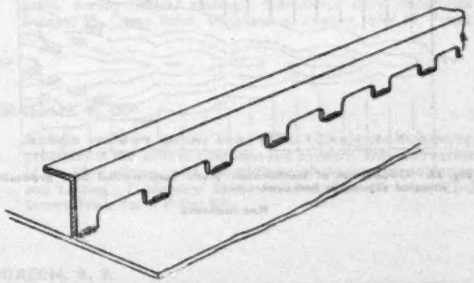

Fig. 12. Scalloped web of stiffener distortion from this design is reduced to minimum

(*a*) *Fillet Welds.* Continuous fillets will produce greater distortion than intermittent of the same leg length.

The fillet welded scalloped stiffener (Fig. 12) produces the least distortion.

(*b*) *Butt Welds.* The extent of distortion is affected by the form of edge preparation, which determines the degree of eccentricity of thermal disturbance in the joint. Plate thickness, area and length have all a marked effect on the extent of distortion likely to occur in welded work. Distortion tends to increase with decrease in thickness and increase in joint length and plate area.

Methods of Counteracting Distortion

Methods may be considered as pre-welding and post-welding.

(*a*) Objective methods are those precautions applied before and during welding, resulting in satisfactory steelwork.

(*b*) Subjective methods are those applied to rectify distortion after welding.

(*a*) Pre-welding methods may be termed (i) *Design* and (ii) *Welding Procedure*:—

(i) Design should aim to produce:

As small a volume of weld as possible.

Welds balanced on opposite sides of the structure.

Highest proportion of automatic welding in preference to hand welding.

Reduction in number of joints to practicable minimum (*i.e.* use broadest and longest possible plate).

Structure in which the portion likely to distort is held rigid by perpendicular members.

Square downhand butts with deep penetration in preference to Vee butts.

Elimination of composite welded and riveted joints.

(ii) Welding Procedure should include:—

Largest practical electrode for the particular welds.

Penetration in preference to compensating reinforcement.

Automatic welding in preference to hand welding for butts and longitudinal seams.

Methods of restraint such that two structures having eccentric welds are fixed back to back and welding is balanced to introduce contra-distortion.

Deposition of weld-metal in structures having eccentric welded joints on the opposite side of the joint so that shrinkage of the deposit counteracts that of the welds.

Use of step-back welding procedures for long Vee butts for thicker plating.

(*b*) Post-welding methods comprise mainly intentionally induced shrinkage of the areas of metal in the structure which is in compression due to the shrinkage of weld metal surrounding and adjacent to it.

There are two typical conditions of distortion observed:—

(i) "Panelling," where the edges of the plate area have shrunk causing the compressed centre area to bulge or indent.

(ii) Deflection of beams due to contraction from eccentrically positioned welds.

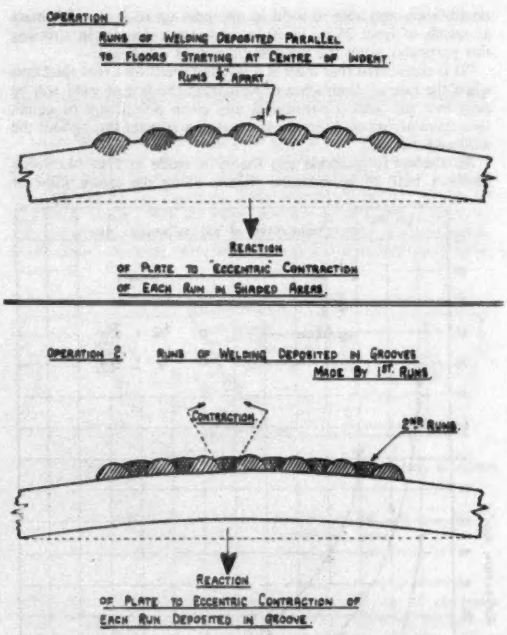
OPERATION 1.
RUNS OF WELDING DEPOSITED PARALLEL TO FLOORS STARTING AT CENTRE OF INDENT.
RUNS 4" APART
REACTION
OF PLATE TO ECCENTRIC CONTRACTION OF EACH RUN IN SHADED AREAS.
OPERATION 2.
RUNS OF WELDING DEPOSITED IN GROOVES MADE BY 1ST. RUNS.
CONTRACTION.
2ND RUNS.
REACTION
OF PLATE TO ECCENTRIC CONTRACTION OF EACH RUN DEPOSITED IN GROOVE.

Fig. 15. Welding procedure used to "Pair" indents in plating.

In case (i) shrinkage may be effectively induced by the procedure illustrated in Fig. 15. The extent of welding required to straighten plating depends on the extent of misalignment, plate thickness and the rigidity of the structure. The procedure should be applied only by operatives having experience of this class of work. Shrinkage may be induced by applying the oxy-acetylene flame to areas about 1 in. diameter, which are then allowed to cool quickly. Again experience in this process is necessary.

In the case of (ii), deflection may be taken out by deposition of weld on the side of the beam opposite to the weld.

It is considered that the above methods should be applied only to members of minor structural importance. In addition the application should be controlled by a responsible and experienced operative. Excessive application of contra-distortion methods may result in serious damage to the structure.

Distortion may be considered the demerit as against the merit of welding. It may not miraculously disappear, but will require to be overcome by the users of welding. The problem must be tackled in the same manner as many other engineering problems which proved difficult in the past and have been overcome by what are now regarded as an accepted standard methods involved in the particular process.

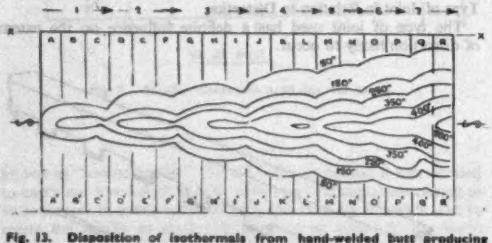

Fig. 13. Disposition of isothermals from hand-welded butt producing unequal expansion and contraction.

Run sequence

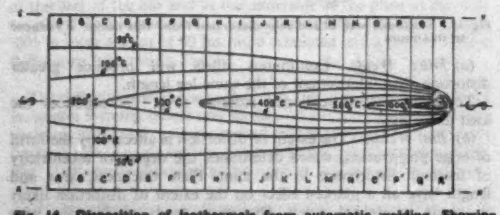

Fig. 14. Disposition of isothermals from automatic welding. Showing relatively uniform expansion and contraction.

Acknowledgment

The writer wishes to record appreciation to Messrs. Alexander Stephen & Sons Ltd., for their permission to publish this paper.

Latest Additions to the Library

AS a supplement to the Library catalogue, this section of the *Transactions* contains particulars of books and pamphlets added to the Library during the second quarter of this year. The books, pamphlets and periodicals specified are available on loan to members of the Institute.

Publications preceded by an asterisk are donations to the Library from authors or publishers; those preceded by a dagger are donated by the James F. Lincoln Arc Welding Foundation.

***ALUMINIUM DEVELOPMENT ASSOCIATION**

(a) Aluminium alloy castings. Illus. 1950. (Information Bulletin No. 17). **(b) Aluminium alloy sections for road vehicle bodies with notes on design and practice.** Illus. 1950. Publishers: Aluminium Development Association, 33, Grosvenor Street, London, W.1. Price: (a) 1/-; (b) issued free on application.

***AMERICAN WELDING SOCIETY**

(a) C.1.1-50. Recommended practices for resistance welding. (b) C.2.1-50T. Recommended practices for metallizing. Part. 1A.: Metallizing shafts or similar objects. Part 11: Metallizing: safety recommendations. Publishers: American Welding Society, 33, West 39th Street, New York, 18. Price: (a) 1 dollar; (b) 75 cents.

AVERY, H. S.

Hard surfacing by fusion welding. Illus. 1947. (This volume contains sections on the advantages of hard facing; hardness; abrasion and impact; abrasion testing; galling; materials for hard facing; and welding techniques. The bibliography comprises 40 references.) Publishers: American Brake Shoe Company, 230, Park Avenue, New York, 17. Price: 25/-.

***BRAITHWAITE & CO., ENGINEERS, LTD.**

Notes on the welding of steel structures. Illus. 1950. (Comprises diagrams and data on typical fillet welds, strength of fillet welds, typical butt welds, deep penetration butt welds, make up of plate girders, rigid frame construction, rocker bearings, distortion from welding, welded lattice girder bridge members, welded bridge bearings, estimation of electrode quantities, and conversion of welding data to metric units.) Publishers: Braithwaite & Co., Engineers, Ltd., Kings House, Haymarket, London, S.W.1.

BRAITHWAITE, R. G., and DAVIES, D. J.

Welding in bridgework and allied structures. (*Reprinted from Trans. Inst. Welding, Dec. 1949, and Feb. 1950*). Publishers: Institute of Welding, 2, Buckingham Palace Gardens, London, S.W.1. Price: 2/6.

BRITISH STANDARDS INSTITUTION

(a) No. 18.—1950. Tensile testing of metals. (b) No. 499. Part 2.—1948. Glossary of welding and cutting terms. Part 2. Terms relating to weld imperfections appropriate for radiographic examination. (c) No. 1453.—1950. Steel filler rods for gas welding of mild steel. Publishers: British Standards Institution, 28, Victoria Street, London, S.W.1. Price: (a) and (b) 2/6; (c) 1/-.

***BRITISH WELDING RESEARCH ASSOCIATION**

T.22. Memorandum on faults in arc welds in mild and low alloy steels. Illus. (*Reprinted from Welding Research, 1950, June.*) Publishers: British Welding Research Association, 29, Park Crescent, London, W.1. Price: 2/6.

***ELEKTRISKA SVETSNINGSAKTIEBOLAGET**

Tillampäd bagsvetsning: application of arc welding. 1950. (This volume contains a number of papers awarded prizes in a Jubilee Competition held by the Swedish company, Esab, manufacturers of OK electrodes. They deal with the following subjects: welded machinery, bridges and buildings, locomotives, and pressure vessels. Included are contributions entitled: "All-Welded Lattice Girders for Railway Bridges constructed in Steel ST N," by M. Ros, F. Bühler and G. Ceradini; "Electric Arc Welding of Thick Sections of High Tensile Structural Steel," by M. Ros and R. Montandon; "Static and Fatigue Tests with Different Types of Cover Straps," by M. Ros and G. Ceradini. All these papers, which are profusely illustrated, are published in Swedish and English.) Publishers: Elektriska Svetsningsaktiebolaget, Göteborg, Sweden. A limited number of copies are for sale at Welding Supplies Ltd., Beechings Way, Gillingham, Kent. Price: 21/-.

RURAL INDUSTRIES BUREAU

Oxy-acetylene welding for country smiths. Illus. 56 pp. 1950. (Data on gas welding plant, steel welding, repairs to iron castings by fusion welding, bronze welding, rebuilding of worn parts, testing welds, costing.) Publishers: Rural Industries Bureau, 35, Camp Road, Wimbledon, London, S.W.19. Price: 1/3.

GRAHAM, F. D.

Audels welders guide. Illus. 1950. (Comprises all welding processes in the form of questions and answers. This is a reprint of the 1945 edition, with the addition of chapters on soldering and brazing.) Publishers: Theo. Audel & Co., 49, West 23rd Street, New York. Price: 8/6.

***GREEN, R. S.**

(a) Welding patent classification in the A. F. Davis welding library. (*Ohio State University Studies, Jan. 1950.*) **(b) Holdings in the A. F. Davis welding library.** (*Ohio State University Studies, March, 1950.*) Publishers: Engineering Experiment Station, Ohio State University, Columbus 10, Ohio. Price: (a) 75 cents; (b) 50 cents.

***INSTITUTE OF BRITISH FOUNDRYMEN**

Repair and reclamation of grey iron castings by welding

and allied methods: report of Sub-Committee T.S.23 of the Technical Council. 1950. (Comprises gas welding with cast iron filler rods, bronze welding, arc welding with ferrous and non-ferrous electrodes, and burning-on.) Publishers: Institute of British Foundrymen, St. John Street Chambers, Deansgate, Manchester, 3.

INTERNATIONAL ASSOCIATION FOR BRIDGE AND STRUCTURAL ENGINEERING

Publications. Ninth Volume. 1949. Publishers: General Secretariat, International Association for Bridge and Structural Engineering, Zurich. Price: 45 Swiss francs.

KODAK LTD.

Kodak X-ray manual: industrial edition. Illus. 1942. Publishers: Kodak Ltd., Kodak House, Kingsway, London, W.C.2. Price: 2/6.

LLOYD'S REGISTER OF SHIPPING

Rules for welded pressure vessels. Illus. 1950. Publishers: Lloyd's Register of Shipping, 71, Fenchurch Street, London, E.C.3. Price: 2/6.

***NATIONAL PHYSICAL LABORATORY**

Report for the year 1948. 1950. Publishers: H.M.S.O., York House, Kingsway, London, W.C.2. Price: 1/9.

NORTHERN ADVISORY COUNCIL FOR FURTHER EDUCATION

Third annual report, 1949-1950. Publishers: Northern Advisory Council for Further Education, 43, Eldon Place, Newcastle-upon-Tyne, 1.

***THE ROYAL SOCIETY.**—*INFORMATION SERVICES COMMITTEE*

A list of British scientific publications reporting original work or critical reviews. 1950. Publishers: Cambridge University Press, Bentley House, 200, Euston Road, London, N.W.1. Price: 2/6.

WECK, R.

An account of M. Henri M. Schnadt's ideas on the strength of materials, and his testing methods. (*Reprinted from Trans. Inst. Welding, Apr. 1950.*) Publishers: Institute of Welding, 2, Buckingham Palace Gardens, London, S.W.1. Price: 2/-.

TRADE CATALOGUES

A.I. ELECTRIC WELDING MACHINES LTD.

Electric welding machines. 1950. (Data on the latest types of resistance welders, comprising spot welders, mitre welders used in the manufacture of metal windows, flash butt welders for general purposes, tubular sections, rim sections, pipes and flanges, etc.) Address: 64, Victoria Street, London, S.W.1.

ARCOS CORPORATION

Low hydrogen type electrode data sheets: (1) Tensilend 70, AC-DC (mild steel); (2) Tensilend 100, AC-DC (Ni-Mo-V); Tensilend 120 DC (Ni-Mo-V). Address: 1500, South 50th Street, Philadelphia.

GEBR. BÖHLER & CO.

Böhler Edel-Schweissdrähte für allgemeine Verwendung und für Sonderzwecke. 1950. (A comprehensive catalogue of electrodes and welding rods for arc, gas, submerged arc, and Elin-Hafergut welding, and hardfacing.) Address: Elisabethstrasse 14, Vienna.

CURTIS MANUFACTURING CO. LTD.

Curtis resistance and control gear for all purposes. Illus. 1950. Address: 26-28, Paddenswick Road, Hammersmith, London, W.6.

W. EDWARDS & CO. (LONDON) LTD.

A digest of Edwards high vacuum equipment for industry, research, education. Illus. 1950. Address: Worsley Bridge Road, London, S.E.26.

HANCOCK & CO. (ENGINEERS) LTD.

Hancock cutting machines. Illus. 1950. (The latest models of oxygen cutting and profiling machines.) Address: Progress Way, Croydon, Surrey.

KODAK LTD.

(1) Can industrial radiography help you? (2) Kodak industrial X-ray catalogue: materials and equipment for industrial radiography. (3) Price list, 1950. Address: Kodak House, Kingsway, London, W.C.2.

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Association Notes

Experiments for the Determination of the Influence of Residual Stresses on the Fatigue Strength of Structures.

The report by Professor M. Roš, of Zürich, published in this issue, was submitted to the Commission on Residual Stresses and Stress Relieving of the International Institute of Welding at the meeting in Paris in June, 1950. A series of fatigue tests were undertaken by Professor Roš with the object of obtaining an indication of the effect of residual stresses on fatigue strength. Residual stresses were introduced by forcing a plug into a round hole made in a flat plate, by pinning together two pieces of plate whilst under stress and by welding plugs into holes trepanned in flat plates. The conclusions are that the effect of residual stresses on fatigue strength is not likely to exceed 8 per cent.

A Review of Recently Published Information on the Spot Welding of Light Alloys.

The purpose of this review is to provide a summary of existing information on spot welding of light alloys as related to the researches being undertaken by British Welding Research Association at present. As the field of past investigation is so wide, only information appertaining directly to the research programme has been considered.

A brief summary of the types of spot welding machines that are in present use is included. This is followed by a review of information on the variables of welding machines and their effect on the production of good welds.

A section on surface preparation prior to welding is also included.

The report was prepared for the L.R. Committee of B.W.R.A. on the Resistance Welding of Light Alloys; members of the Committee are as follows:—

Dr. E. G. West (Chairman), Aluminium Development Association;
R. W. Ayers, Sciaky Electric Welding Machines, Ltd.;
W. V. Binstead, Northern Aluminium Co., Ltd.;
H. Brooks, Royal Aircraft Establishment;
B. Evans, Ministry of Supply;
E. A. G. Liddiard, Fulmer Research Institute;
R. F. Tylecote, Royal School of Mines;
W. S. Simmie, Pressed Steel Co., Ltd.;
H. J. Brooks, Percival Aircraft Ltd.;
E. J. Keefe, British Insulated Callender's Cables Ltd.;
P. W. Hyde, Westland Aircraft, Ltd.;
B. H. Le Pine Williams.

B.O.C. Welding Research Prize.

The Council of the British Welding Research Association have awarded the 1949 Welding Research Prize of £100 to Dr. K. Winterton, Mr. J. G. Ball and Mr. C. L. M. Cottrell for their joint paper entitled "A New Weldability Test for Magnesium Alloy Sheet." This prize has been donated by the British Oxygen Co. Ltd., who have kindly offered to provide a Prize Fund for a competition relating to welding for three years.

The Council have decided that the closing date for entries for the 1950 competition shall be extended to 31st December, 1950. A single prize of £100 is offered again this year and will be awarded for the best paper submitted on a research into welding or its applications. Full details relating to this competition can be obtained from the Secretary, British Welding Research Association, 29, Park Crescent, London, W.1.

A few of the more recent B.W.R.A. Publications

RECOMMENDATIONS FOR THE STANDARDISATION OF THE RADIOGRAPHIC EXAMINATION OF WELDED JOINTS IN MILD STEEL PRESSURE VESSELS

These recommendations provide a direct practical lead towards a uniformly high standard of radiographic procedure in British Industry. The recommendations cover plant, protection of personnel, radiographers, radiographic technique, numbering of radiographs and a code for interpretation of radiographs.

Price 1/6, post free.

PHOTOGRAPHIC ASPECTS OF THE RADIOGRAPHY OF WELDED HIGH PRESSURE VESSELS

The purpose of this paper is to review the desirable characteristics in the sensitive materials used and to set out recommendations on their handling and processing. The paper covers choice of photographic materials, handling and processing X-ray films, confusing shadows in weld radiographs, formulae of solutions for processing X-ray films and is illustrated by 23 plates and diagrams.

Price 2/-, post free.

DUPLICATED REPORTS

The following have not been printed but a few copies are available in typescript form:—

FE.1/18—"The Determination by Relaxation Methods of Elasto-Plastic Stresses in Two Transversely Loaded Beams." By J. Heyman, M.A.

Price 2/-, post free.

FE.1/19—"The Variation of Mean Floor Loads with Area." By M. R. Horne, M.A.

Price 1/-, post free.

FE.1/20—"The Plastic Theory of Bending of Steel Beams, with Particular Reference to the Effect of Shear Forces." By M. R. Horne, M.A.

Price 2/6, post free.

All the above reports are obtainable from the British Welding Research Association, 29, Park Crescent, London, W.1. A full list of publications is available on request.

R61

Experiments for the Determination of the Influence of Residual Stresses on the Fatigue Strength of Structures

By Prof. Dr. M. Roš

Report submitted to Commissions 10 - 11 of the International Institute of Welding

INTRODUCTION

There are two ways of introducing residual stresses in a part; either by means of a non-uniformly distributed cold deformation of the body or by means of non-uniform shrinkage of different parts when the piece is cooled down from a higher temperature (residual stresses due to cold deformation and thermal shrinkage). In both cases other changes may be produced in the material depending on the temperature, such as strain hardening, recrystallisation, precipitation, etc. In the interpretation of the results of experiments these various influences must be taken into consideration, but this is not always easy because the testing methods which are required for this purpose are either very complicated and are only available at a limited number of laboratories or else they are still in the state of development[1]. It is, however, generally known that every deformation exceeding the elastic limit is accompanied by an increase in hardness which, depending on the structure, may be anisotropic and which is due generally to disturbances in the crystal lattice[2], such as dislocations and blockages. Precipitation from supersaturated solution (ageing) may contribute to this increase in hardness.

At present it is customary in the investigation of materials with regard to their fatigue behaviour to consider only the strength and to ignore the ability to deform. This may lead to a one-sided assessment of different treatments applied to structural assemblies. In the case of impact loading and in the case of very considerable deformations in consequence of restraints, where it is in the first instance a question of sustaining deformations in excess of the elastic limit, it may become necessary to consider the adaptability of a connection to the boundary conditions in addition to its fatigue strength[3]. In order to bring out these differences which depend on the testing conditions, a number of exploratory tests were carried out at the Federal Institute for Testing Materials (FITM) with structural parts in which constraints were introduced in different ways. The following is a report of these tests in detail. These experiments cannot claim to be of general validity. They were designed to facilitate recognition of the various accompanying phenomena. It is, of course, understood that these accompanying phenomena can occur in varying degrees depending on the particular properties of the material used in the investigation.

1. FLAT PLATE SPECIMENS WITH A DRILLED HOLE AND WITH A FITTED- OR SHRUNK-IN PLUG OR A PRESSED-IN CONICAL DOWEL

The flat steel specimens of 50×10 mm. used in this investigation had the following properties in the as-rolled condition:—

Limit of Proportionality	..	σ_P = 26·8 kg. per sq. mm.
Upper Yield Point	..	σ_{So} = 27·2 kg. per sq. mm.
Ultimate Tensile Strength	..	β_z = 40·2 kg. per sq. mm.
Reduction of Area	..	ϕ = 58·0 per cent.

For the fatigue tests, carried out at a frequency of 350 cycles per minute up to 1,000,000 cycles to fracture in an Amsler pulsator, the test pieces were machined all over and exhibited in this condition, without a hole, a basic tensile fatigue strength ${}_{o}\sigma\,\delta$ = 30·7 kg. per sq. mm. The following fatigue tests were carried out with this material in the basic tensile range with the lower limit of loading equal to zero.

(a) Flat specimen machined all over with a drilled hole of 10 mm. diameter in the centre of the specimen

The basic tensile fatigue strength (the average stress of the net cross section for the upper limit of loading) was obtained as ${}_{o}\sigma\,\delta$ = 20·5 kg. per sq. mm. The theoretical stress concentration α_k has been obtained α_k = 2·52 for a ratio of width to thickness of d/b = 1/5. The notch effectiveness $\beta_k = \frac{30{\cdot}7}{20{\cdot}5} = 1{\cdot}5$, and from this the notch sensitivity is obtained[4],

$$\eta_k = \frac{\beta_k - 1}{\alpha_k - 1} = \frac{0{\cdot}5}{1{\cdot}52} = 0{\cdot}33,$$

which is a relatively good value for ordinary mild steel.

(b) Flat specimens as under (a) with a loose plug from the same material in the hole

The fatigue test gave the same result for the basic tensile fatigue strength as in the case of the empty hole under (a), namely ${}_{o}\sigma\,\delta$ = 20·0 kg. per sq. mm., despite the fact that the plug was gripped in the hole already after the first cycle of loading.

(c) Flat specimen as under (a) with a plug of the same material shrunk into the hole at 200 deg. C. and 400 deg. C. respectively

The calculated shrinkage stresses in this case were approximately: 16 and 32 kg. per sq. mm. respectively radial for an excess diameter of ·15 and ·30 per cent. respectively with the modulus E = 21,000 kg. per sq. mm. On the assumption of purely elastic behaviour the stress in the wall of the hole can be calculated as follows:—

$\sigma_t \cong \sigma_{\text{radial}} \times \sqrt{3}$ = 28 and 56 kg. per sq. mm. respectively.

It must be assumed from this that in the case of the larger plug the yield point has been exceeded at the point of stress concentration already prior to the fatigue test. The fatigue strength values which have been obtained for these flat specimens for 1,000,000 loading cycles were:

${}_{o}\sigma\,\delta$ = 22·6 and 24·1 kg. per sq. mm. respectively.

Although the shrinkage stress in the tangential direction was a tensile stress and although the stress was above the yield point of the material, the basic tensile fatigue strength of the specimen was, nevertheless, raised by shrinking a plug into the hole. The increase in fatigue strength in the present case was 17 per cent. This apparent paradox can be explained if it is assumed that the stress amplitude in fatigue loading is considerably smaller than in the case of the empty

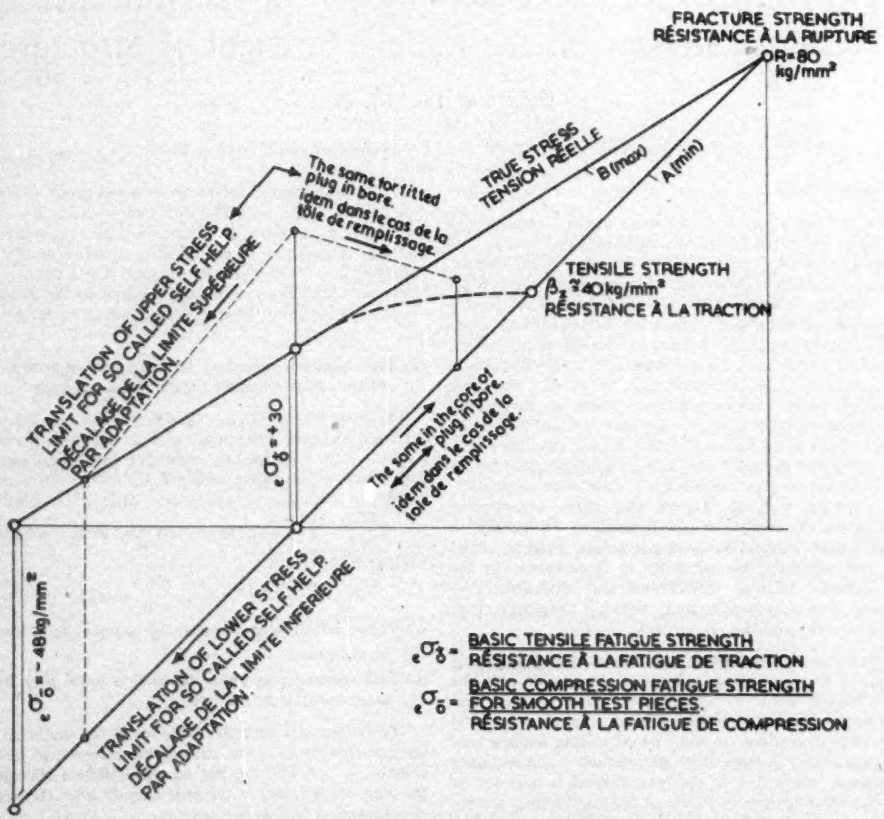

FRACTURE STRENGTH
RÉSISTANCE À LA RUPTURE
R=80 kg/mm²
TRUE STRESS
TENSION RÉELLE
B(max)
A(min)
The same for fitted plug in bore.
idem dans le cas de la tôle de remplissage.
TENSILE STRENGTH
RÉSISTANCE À LA TRACTION
TRANSLATION OF UPPER STRESS LIMIT FOR SO CALLED SELF HELP.
DÉCALAGE DE LA LIMITE SUPÉRIEURE PAR ADAPTATION.
The same in the core of plug in bore.
idem dans le cas de la tôle de remplissage.
TRANSLATION OF LOWER STRESS LIMIT FOR SO CALLED SELF HELP.
DÉCALAGE DE LA LIMITE INFÉRIEURE PAR ADAPTATION.
BASIC TENSILE FATIGUE STRENGTH
RÉSISTANCE À LA FATIGUE DE TRACTION
BASIC COMPRESSION FATIGUE STRENGTH
FOR SMOOTH TEST PIECES.
RÉSISTANCE À LA FATIGUE DE COMPRESSION

Fig. 1. Goodman diagram: material St. N. machined all over. True stress limits A and B for perforated bars with and without fitted plug in bore.

hole when the relative movement between plug and bore is prevented. In the limiting case the difference between upper and lower limit stress $\sigma_o - \sigma_u$ could be $(\sigma_o - \sigma_u) = \frac{P}{F_{gross}}$ instead of $\frac{P}{F_{nett}} \cdot \alpha_k$, where F_{gross} and F_{nett} are gross and net sections, P is the applied load and α_k the stress concentration factor. The value P/F_{gross} was not quite reached in the present cases, proof of which can be seen in the fact that cocoa* could be observed after all the fatigue tests described under (b) and (c). Since, however, the cold deformation was relatively small, approximately 0·1 per cent., the increase in the fatigue strength which has been found must be attributed in the first instance to a modification in the stress distribution prior to and during the fatigue test. The residual stresses increase in the present case the lower limit stress at the point of the maximum stress concentration, but they decrease the true stress amplitude to such an extent that the upper limiting line of the Goodman diagram is reached only for larger applied loads (Fig. 1). We have, therefore, here the reverse case from that of the so-called self-help or adaptation[5], namely, the mean stress is displaced into the tensile region, but the stress amplitude is diminished at the same time.

* The name "cocoa" is given to a fine reddish powder, ferrous oxide, which is the product of frictional oxidization (dry or fretting corrosion) and is produced when very small movements occur between two closely fitting surfaces clamped together.

(d) Flat specimen as under (a) with pressed-in conical dowel taper approximately 1 : 50

The hardened dowel was driven into the hole in this case so that Lüders lines appearing on the surface extended into the vicinity of the edges of the test pieces. The basic tensile fatigue strength for these test pieces was:

$$_{e}\sigma\,\delta = 25{\cdot}0 \text{ kg. per sq. mm.}$$

This corresponds to an increase in fatigue strength of 22 per cent. In order to determine the load in the dowel when it was pressed-in, two series of experiments were carried out with the same material for which the basic tensile fatigue strength $_{e}\sigma\,\delta = 22{\cdot}2$ kg. per sq. mm. had been obtained for drilled and conically reamed test pieces. If a conical dowel was pressed-in by applying a load of 2·1 tons without using a lubricant and without degreasing the surfaces specially, the basic tensile fatigue strength was $_{e}\sigma\,\delta = 28{\cdot}3$ kg. per sq. mm., that is, 27 per cent. more. If, however, the conical dowel was pressed out again and the bore was polished with emery paper, the basic tensile fatigue strength was only $_{e}\sigma\,\delta = 25{\cdot}4$ kg. per sq. mm., that is, the basic tensile fatigue strength was increased by 14 per cent. in consequence of the cold deformation of the wall of the hole and the residual stresses accompanying this deformation. We can recognise from this that part of the improvement of the fatigue strength is due to the work hardening and residual stresses in the wall of the hole, and another part is due to the modification of the stress amplitude in consequence of the action of the dowel during the fatigue test. Each of the two effects alone amounts to a maximum of 14 per cent. and this for relatively thin plates of 10 mm. thickness.

2. FLAT SPECIMENS MACHINED ALL OVER. CROSS SECTION 100 BY 20 MM., WITH A BORE OF 20 MM. DIAMETER IN THE CENTRE OF THE SPECIMEN WITH AND WITHOUT ENLARGING HOLE BY PRESSING

In order to determine the influence of increasing the bore by cold pressing, specimens of larger thicknesses were used. The properties of the material in the longitudinal direction were as follows:—

Square test pieces of 20 by 20 mm. gave the following properties:—

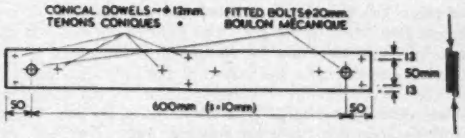
Limit of Proportionality	σ_P	= 24·0 kg. per sq. mm.
Upper Yield Point	σ_{su}	= 24·4 kg. per sq. mm.
Ultimate Tensile Strength	β_k	= 35·9 kg. per sq. mm.
Reduction of Area	ϕ	= 70·0 per cent.

Round test pieces of 10 mm. diameter with screwed ends gave the following properties:—

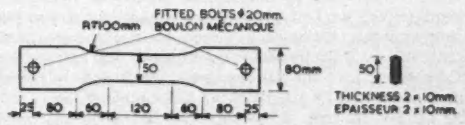
Limit of Proportionality	σ_P	= 30·2 kg. per sq. mm.
Upper Yield Point	σ_{so}	= 30·2 kg. per sq. mm.
Lower Yield Point	σ_{su}	= 24·3 kg. per sq. mm.
Ultimate Tensile Strength	β_k	= 35·8 kg. per sq. mm.
Reduction of Area	ϕ	= 75·0 per cent.

As is well known the upper yield point can only be determined accurately with test pieces which are accurately axially loaded. The basic tensile fatigue strength of 20 mm. thick test pieces with conical round holes not increased by pressing was $_{e}\sigma\,\delta = 19{\cdot}3$ kg. per sq. mm., as compared with that of the smooth unperforated test pieces $_{e}\sigma\,\delta = 32{\cdot}9$ and 33·9 kg. per sq. mm., which gives a mean of 33·4 kg. per sq. mm. The stress concentration factor is also in this case $\alpha_k = 2{\cdot}52$ because of the same width to thickness ratio of $d/b = 1/5$. The notch effectiveness, however, is $\beta_k = 32{\cdot}9/19{\cdot}3 = 1{\cdot}7$, from which the notch sensitivity of the material is obtained as 46 per cent. This material is, therefore, considerably more notch sensitive than the 10 mm. thick material.

Further test pieces were pressed out by means of a conical dowel of 1/50 taper by using the following forces P = 5·5, 8·0 and 11·0 tons, in which case the dowel was pressed out again and the wall of the bore was polished with emery paper. In the last case when the dowel was pressed-in with a force of 11 tons, the Lüders lines reached the edges of the specimen. The basic tensile fatigue strength of the test pieces treated in this way with empty holes was independent of the degree of pressing and was practically the same as that of the specimen with the bore not increased by pressing, namely $_{e}\sigma\,\delta = 19{\cdot}8$, 19·9 and 20·0 kg. per sq. mm., as compared with $_{e}\sigma\,\delta = 19{\cdot}3$ kg. per sq. mm. for the case of the bored specimen without opened-up bore. It can be recognised from this that cold working alone does not produce an increase in the basic tensile fatigue strength in this more notch-sensitive material. This is a warning against the indiscriminate application of cold work for the purpose of increasing the fatigue strength or the fatigue life of structural parts. The test pieces were subjected to the fatigue test soon after the cold deformation had been produced. The fatigue test, however, required a time of between seven to eleven days for the 10 mm. thick test pieces and two-and-a-half to four-and-a-half days for the 20 mm. thick test pieces so that natural ageing could already exercise a certain influence.



(*a*) Pair of flat specimens stressed in bending and joined by four conical dowels.



(*b*) Pair of flat specimens stressed in bending and joined in this condition by two weld beads.

Fig. 2. Pair of flat specimens with locked-up stresses.

3. PAIR OF FLAT SPECIMENS AFFLICTED WITH INTERNAL RESTRAINT

The test pieces up to now had consisted of one specimen with a hole. In order to determine the effect of internal restraint in a connection, two flat specimens, one on top of the other, were elastically pre-stressed by bending and were restrained in this position either by means of conical dowels or by means of longitudinal edge welds and subjected to fatigue tests (Fig. 2). The material was the same 10 mm.

thick plate as that used in previous tests and for which the basic tensile fatigue strength—for test pieces with smooth surfaces machined all over—had been obtained as $_{o}\sigma\,\delta = 34{\cdot}4$ kg. per sq. mm. The static strength properties which had also been determined for flat specimens machined all over were as follows:—

Limit of Proportionality	..	$\sigma_P = 28{\cdot}5$ and 30·5 kg. per sq. mm. respectively
Upper Yield Point	.. ..	$\sigma_{So} = 29{\cdot}3$ and 32·3 kg. per sq. mm. respectively
Ultimate Tensile Strength	..	$\beta_z = 41{\cdot}2$ and 40·8 kg. per sq. mm. respectively
Reduction of Area	.. ..	$\phi = 57{\cdot}0$ per cent.

(a) Pair of flat specimens joined by four conical dowels

The cross section of the specimen was 76·0 by 9·7 mm., from which the two holes of 11·8 mm. diameter must be deducted (Fig. 2a). The calculated basic tensile fatigue strength of the pair of specimens connected by dowels and with polished surfaces amounted to $_{o}\sigma\,\delta = P/Fnett = 25{\cdot}3$ kg. per sq. mm. in the case of specimens without internal restraint. In the case of the elastically pre-stressed pair of specimens which had been bent so as to produce stresses nearly equal to the yield point of the material, the fatigue strength was only $_{o}\sigma\,\delta = 17{\cdot}8$ kg. per sq. mm. Internal restraint in riveted, bolted or screwed connections reduces the basic tensile fatigue strength very considerably, in the present case nearly 30 per cent. This must be attributed to the edges of the dowels and the fretting in consequence of the relatively large relative movement of the individual parts in this type of connection. The pre-stress of the flat specimens in this case was so large that when the holes were bored when the specimens were pre-stressed, the Lüders lines extended almost over the entire width of the specimen.

(b) Pair of flat specimens joined by two longitudinal welds

Since in the case of unmachined welds the weld itself constitutes the weakest point in the connection, it was not necessary in this case to machine the surfaces of the specimens as carefully as in the preceding experiments. The basic tensile fatigue strength of the flat specimens which had only been roughly treated with emery paper was obtained as $_{o}\sigma\,\delta = 30{\cdot}2$ kg. per sq. mm. When two such flat specimens of 50 by 10 mm. cross section were joined without introducing internal restraint by means of longitudinal welds along the edges (Fig. 2b), the basic tensile fatigue strength was only $_{o}\sigma\,\delta = 19{\cdot}1$ kg. per sq. mm. One may be sure in this case that the beginning of the fatigue failure will be located in the weld. A similar pair of specimens which had been joined in the same way by longitudinal welds but which had been internally pre-stressed up to half the yield point of the material, gave a basic tensile fatigue strength of approximately $_{o}\sigma\,\delta = 17{\cdot}5$ kg. per sq. mm., and in the case of internal stresses equal to the yield point of the material even more, namely, $_{o}\sigma\,\delta = 19{\cdot}8$ kg. per sq. mm., which corresponds to the basic tensile fatigue strength of the pair of specimens joined without internal restraint if one considers the relatively large scatter of the experimental results obtained for welded connections. Since in this type of joint the relative movements between the plates are small, so that no additional damage occurs in the course of the fatigue test from fretting, the fatigue strength suffers no additional decrease in consequence of fretting. This represents a very great advantage of welding in comparison with riveting. It must be admitted, however, that the reaction stresses due to internal restraint have presumably disappeared or have been considerably reduced in consequence of welding, so that from the present results it is impossible to draw general conclusions without extensive measurements of the residual stresses existing after welding and during the fatigue test.

4. COLD STRAIGHTENED RECTANGULAR TEST PIECES ORIGINALLY SEVERELY CURVED

It is well known that cold straightened bars are afflicted with residual stresses. Residual compressive stresses remain in the tension zone, and in the compression zone such high tensile stresses occur that the hooks at the ends of concrete reinforcing bars or hooks for attaching rain water gutters may break in the compression zone already when the load is taken off and without any appreciable external loading. This is a consequence of the anisotropy of the material with respect to its remanent ability to deform caused by the preceding cold deformation[6].

The test pieces were cut from a plate of 24 mm. thickness with the following properties:—

Limit of Proportionality	..	$\sigma_P = 19{\cdot}2$ kg. per sq. mm.
Upper Yield Point	.. ..	$\sigma_{So} = 24{\cdot}4$ kg. per sq. mm.
Ultimate Tensile Strength	..	$\beta_z = 42{\cdot}1$ kg. per sq. mm.
Reduction of Area	.. ..	$\phi = 56{\cdot}0$ per cent.

A number of strips of 30 mm. width were bent cold and then normalised whilst bent at a temperature of 920 deg. C. for thirty minutes and cooled in air, and after normalising they were cold straightened. Other strips were subjected to the same heat treatment without having been previously bent. From these strips test pieces were made by machining all over with a cross section of 30 by 23 mm. in the parallel portion. The cold stretching of the extreme fibres of the bent specimens for a radius of curvature of the neutral axis of $r = 70$ mm. was

$$K = 50 \times \frac{s}{r} = 50 \times \frac{23}{70} = 16{\cdot}4 \text{ per cent.}$$

The residual stresses in the cold straightened test pieces reached the yield point of the material.

The basic tensile fatigue strength for 1,000,000 loading cycles was $_{o}\sigma\,\delta = 28{\cdot}3$ and 30·4 kg. per sq. mm. respectively for the bars which had not been bent. The corresponding figure for the bars which had been bent, normalised and straightened was $_{o}\sigma\,\delta = 29{\cdot}5$ and 31·3 kg. per sq. mm. respectively.

In all four cases the surfaces of the test pieces were machined all over. These results show that the residual stresses alone, which in the present case after bending reached the yield point of the material and which are both compression and tension, have not noticeably influenced the basic tensile fatigue strength of the machined test pieces because of the property of good mild steel—its adaptability—to reduce the internal stresses, which are not required for equilibrium with the external forces, at the critical points. The possibility, however, that in the present case two opposing influences compensated each other must be taken into account: the cold deformation would be expected to result in an increase of fatigue strength for good material. This effect, however, could be nullified by an unfavourable distribution of residual stresses in the piece. In addition it must be considered that in the present case both cold stretched and cold compressed parts occur in the test piece which, depending on the material, may exhibit different behaviour during the tensile fatigue test.

5. WELDED-IN PLUGS MACHINED ALL OVER, NOT HEAT TREATED

Welding-in of plugs produces very high residual stresses which has been shown in numerous tests and is a well-recognised fact of experience[7]. It must be expected that in view of the high residual stresses in such plugs, fatigue tests with such welded joints should throw light on the significance of residual stresses for the fatigue strength. The tests, however, which can be undertaken are limited by the maximum loads which can be produced in existing testing machines. (Upper limit of loading, maximum 90 tons, maximum cross section which can be gripped 150 by 80 mm., greatest length of test piece 2000 mm.) Part of the residual stresses is lost by machining the surfaces of the test piece but, nevertheless, residual stresses of considerable magnitude remain so that at least a qualitative assessment of the influence under discussion should be possible.

(a) Pilot tests with welded-in plugs

The first exploratory tests were carried out with two test pieces of 130 mm. width and 30 to 28 mm. thickness. The trepanned hole had a diameter of 90 mm. and the plug was welded in with a 60 degree double V-weld. The basic tensile fatigue strength of the material for 1,000,000 loading cycles was

$_{o}\sigma\,\delta$ = 26·7 kg. per sq. mm. for the material with mill scale, and

$_{o}\sigma\,\delta$ = 30·2 kg. per sq. mm. for the material machined all over.

This must be considered as very good for plate material of that thickness. The Vickers-Hardness for 5 kg. load was as follows for the first test-piece:—

in the plate	H = 121—135 kg. per sq. mm.
in the transition zone	H = 143—175 kg. per sq. mm.
in the weld metal ..	H = 164—241 kg. per sq. mm.

These hardness measurements were carried out after the specimen had been broken in fatigue. The weld was examined after the fatigue test by means of four macro-sections which exhibited satisfactory dense appearance. The fractured surface, however, showed an accumulation of pores and other small flaws so that the fatigue failure occurred prematurely after 523,000 cycles at a stress of 19·5 kg. per sq. mm. A second test piece broke after 450,000 cycles at a stress of 17·0 kg. per sq. mm. The fractured surface of this test piece exhibited also weld flaws. These experiments, therefore, did not permit any conclusions to be drawn with regard to the problem under review, since the weld flaws result in differences in the fatigue strength which cannot be anticipated.

(b) Welded-in plugs Secheron first series

The form of the test pieces in this series of tests was the same as that under (a). The only difference was that the weld for the first two tests was a single V-weld of 60 degrees, chipped out with a sealing run at the back, whilst the other two test pieces had been welded with a double V-weld.

The plate material of 30 mm. thickness when tested in the as-rolled condition, that is, with mill scale, had the following properties:—

Limit of Proportionality	σ_P = 20·2 kg. per sq. mm.
Upper Yield Point ..	σ_{S_o} = 24·1 kg. per sq. mm.
Ultimate Tensile Strength	β_z = 41·0 kg. per sq. mm.
Reduction of Area ..	ϕ = 42·0 per cent.

The basic tensile fatigue strength for 1,000,000 cycles was

$_{o}\sigma\,\delta$ = 22·6 kg. per sq. mm. for the material with mill scale

$_{o}\sigma\,\delta$ = 24·0 kg. per sq. mm. for the material machined all over.

The low value obtained for the fatigue strength in the machined condition is due to a defect in the plate.

The Vickers-Hardness for 5 kg. load was as follows for the test pieces with V-welds after the fatigue test:—

in the plate material	123-148 kg. per sq. mm.
in the transition zone ..	122-169 kg. per sq. mm.
in the weld	161-192 kg. per sq. mm.

The variations in hardness of the weld metal are smaller in the present case than they were for the preliminary tests.

The four test pieces gave good basic tensile fatigue strength values.

Test pieces with V-welds and sealing run:

first specimen $_{o}\sigma\,\delta \geqq$ 21·9 kg. per sq. mm. Fracture took place in the enlarged end of the specimen.

second specimen $_{o}\sigma\,\delta$ = 21·9 kg. per sq. mm. Failure took place in the weld.

Specimens with double V-welds:

first specimen $_{o}\sigma\,\delta \geqq$ 23·3 kg. per sq. mm. Failure in the enlarged end of the specimen.

second specimen $_{o}\sigma\,\delta \geqq$ 24·0 kg. per sq. mm. Fracture also in the enlarged end of the specimen.

From the first specimen broken in the enlarged end which was gripped in the testing machine, other specimens were prepared of smaller width for other fatigue tests and for hardness and structural examination. The basic tensile fatigue strength of the test pieces which had been cut from the first test piece were $_{o}\sigma\,\delta$ = 25·3 and 26·2 kg. per sq. mm. respectively, where the wider specimen broke in the weld and the narrower specimen broke in the plate material. We can recognise from this that the basic tensile fatigue strength in the four plug welded specimens lies only very slightly below that of the welded specimens which had been cut from the first specimen. A firm conclusion cannot be drawn, unfortunately, because of the fractures taking place in the enlarged portion of the specimens. The only specimen which broke in the weld, the second specimen, with a single V-weld, however, still showed clearly that there were flaws in the fracture surface.

The residual stresses which were still present after the fatigue test in the first test piece with a V-weld and sealing run, which had broken in the enlarged portion of the specimen, were measured after the fatigue test by means of SR 4 electric strain gauges of 20 mm. gauge length which were attached to the specimen prior to its subdivision into small pieces. Whilst the residual stresses determined in this way were relatively small at the edge of the specimen, they reached values of 10 kg. per sq. mm. tension at a point in the axis of the specimen exactly over the weld on the surface where the sealing run was deposited, and 4 kg. per sq. mm. tension on the reverse side.

(c) Welded-in plugs Secheron second series

In the welded-in plugs of the first series the width of the specimens was only slightly larger than the diameter of the plugs, so that the creation of high residual stresses was not favoured as it is in structures of dimensions which are larger in comparison with the plug. In order to take account of this argument and in order to favour fracture as far as possible in the weld, four further test pieces were made, two relatively narrow ones and two relatively wide ones, all with plugs of 100 mm. diameter. The weld was a 60 degree double V-weld. The cross section at the point of the plug weld was 148 by 15 mm. for the small test pieces and 248 by 14 mm. for the large test pieces.

The plate material of 50 mm. thickness gave the following properties with test pieces machined all over:—

Limit of Proportionality	σ_P	= 20·0 to 21·7 kg. per sq. mm.
Upper Yield Point ..	σ_{So}	= 20·7 to 21·9 kg. per sq. mm.
Lower Yield Point ..	σ_{Su}	= 20·0 to 20·3 kg. per sq. mm.
Ultimate Tensile Strength	β_z	= 39·7 to 40·6 kg. per sq. mm.
Reduction of Area ..	ϕ	= 54·0 to 63·0 per cent.

The basic tensile fatigue strength for 1,000,000 cycles was

$_{o}\sigma\,\hat{\zeta}$ = 21·8 kg. per sq. mm. for the material with mill scale, and

$_{o}\sigma\,\hat{\delta}$ = 28·3 and 29·6 kg. per sq. mm. respectively for the material machined all over.

Micro-tensile specimens cut from the welds gave

Upper Yield Point ..	σ_{So}	= 36·7 to 38·8 kg. per sq. mm.
Ultimate Tensile Strength	β_z	= 52·9 to 55·5 kg. per sq. mm.
Reduction of Area ..	ϕ	= 70·0 to 73·0 per cent.

The basic tensile fatigue strength of the weld metal itself determined in the high-frequency Amsler pulsator was between $_{o}\sigma\,\hat{\zeta}$ = 44·8 and 46·2 kg. per sq. mm. It was therefore higher than that of the plate material even if one considers that the fatigue strength as determined in the high-frequency pulsator is 5 to 10 per cent. higher than that obtained in the low-frequency pulsator.

The basic tensile fatigue strength of the plate material is high, on the average $_{o}\sigma\,\hat{\delta}$ = 29·0 kg. per sq. mm., despite the relatively low upper yield point of $\sigma_{S_{o_u}}$ = 21·0 kg. per sq. mm. It is interesting to point out, even if it is of no immediate concern in the tests with plug welds to be discussed, that the normalising of this plate material influenced the yield point, but had no influence at all on the basic tensile fatigue strength. The values for the normalised material were as follows:—

Limit of Proportionality	σ_P	= 29·9 to 27·7 kg. per sq. mm.
Upper Yield Point ..	σ_{So}	= 29·9 to 27·7 kg. per sq. mm.
Lower Yield Point ..	σ_{Su}	= 25·8 to 26·3 kg. per sq. mm.
Ultimate Tensile Strength	β_z	= 41·8 to 42·5 kg. per sq. mm.
Reduction of Area ..	ϕ	= 55·0 to 41·0 per cent.

Basic Tensile Fatigue Strength .. .. $_{o}\sigma\,\hat{\delta}$ = 29·2 to 30·6 kg. per sq. mm.

The Vickers-Hardness for 5 kg. load determined after the fatigue test was as follows:—

in the plate material	139—157 kg. per sq. mm.
in the transition zone	139—156 kg. per sq. mm.
in the weld metal	158—185 kg. per sq. mm.

The increase in hardness of the plate material in consequence of cold working and ageing as compared with that in the as-rolled condition of 111 kg. per sq. mm., is 25 to 40 per cent.

The basic tensile fatigue strengths of the welded-in plugs were as follows for the two first test pieces:—

for the small test piece $_{o}\sigma\,\hat{\delta}$ = 21·1 kg. per sq. mm. fractured in the weld

for the wide test piece $_{o}\sigma\,\hat{\delta}$ = 22·5 kg. per sq. mm. fractured also in the weld.

The fractures started from small weld flaws.

The second pair of test pieces was supposed to represent the optimum that could be obtained in welding by applying all possible means at one's disposal. The basic tensile fatigue strength of these welded test pieces was obtained as follows:—

$_{o}\sigma\,\hat{\delta}$ = 23·9 kg. per sq. mm. for the small test piece, and
$_{o}\sigma\,\hat{\delta} \geq$ 23·0 kg. per sq. mm. for the wide test piece.

The last test piece did not break in the weld, but in the vicinity of the enlarged end of the test piece where the straight portion changed into the curved portion.

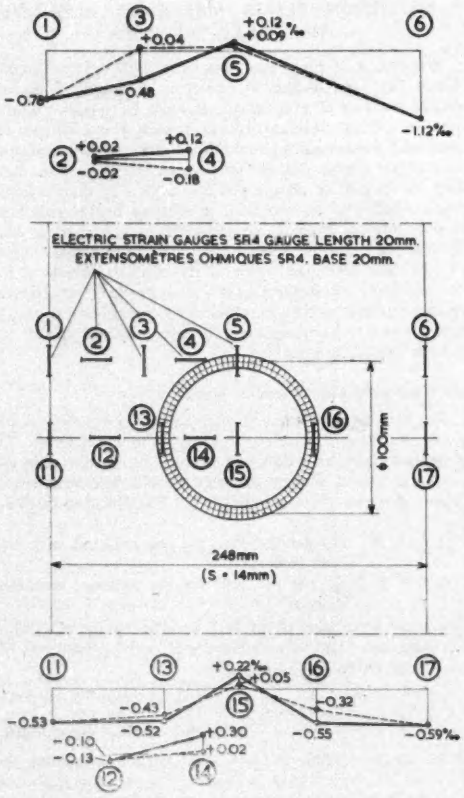


Fig. 3. Plug welded sécheron second series, specimen 4B.

These two last test pieces clearly prove that the width of the test pieces has no noticeable effect on the fatigue strength, at least within the limits of cross section applying in these tests. That very high residual stresses must have been present in these plug welded specimens is shown by measurements which have been carried out with the last specimen which broke in the enlarged end. The residual stresses were determined by means of SR 4 electric resistance strain gauges after the fatigue test, by subdivision (Fig. 3). The maximum value for strain was observed at the edge of the test piece after cutting, and amounted to −0·112 per cent. which corresponds to a residual tensile stress equal to the yield point of this plate material. The weld, on the other hand, showed strains in the tangential direction of only about half that magnitude, namely, a maximum of −0·055 per cent. The plug is subjected to uniform bi-axial pressure corresponding to a dilatation of no more than +0·03 per cent. As has already been stated these residual stresses have been determined after the fatigue test, during which the test piece had sustained the following cycles of stress:—

Upper Limit of Stress kg. per sq. mm.	*Stress Cycles* $\times 10^6$	
1—15	1·144	Load increased
to 1—20	1·115	Load increased
to 1—22	1·102	Load increased
to 1—24	1·180	Load increased
to 1—26	0·010	Fractured in the plate.

The yield point of the plate material, which was only about 20 kg. per sq. mm., was greatly exceeded in these tests, which finds expression also in the increase of hardness in consequence of the cold deformation. It is, of course, understood that these test pieces after having been stressed to such high limits can no longer contain the same residual stresses as those present at the beginning of the fatigue test. At the edge of the specimen they even seem to have changed their sign, because tensile stresses were found there where it must be assumed with certainty that originally compressive stresses must have been present, namely, at the extreme edge of the cross section which passes through the centre of the plug, whilst in the centre of the plug tensile stresses were found corresponding to strains of −0·053 and −0·059 per cent.

When the deformations measured during the subdivision of the test piece with the object of determining the residual stresses are considered as a whole, it appears that there was no equilibrium between the tensile and compressive residual stresses (Fig. 3). It must be considered, however, that in this case, apart from the skin effect determined by X-rays, the stresses are merely those which are present on the surface, whilst in the interior of the test piece entirely different stresses, even tri-axial stresses, may be present. This is the more likely in the present case since the weld was made by depositing a number of beads in succession and the welded seam, of course, was of different width at different depth. Since the weld metal is considerably harder than the plate material (yield point approximately 36 and 20 kg. per sq. mm.), it is inevitable that the residual stresses at the end of the fatigue test must depend to a very large extent on the degree to which the yield point of the parent plate, which is the softer part of the test piece, has been exceeded. This circumstance makes it exceedingly difficult to take the residual stresses into account and to assess their influence on the fatigue strength to be expected, so that one has to take recourse to direct experiments, even when in previous similar cases extensive series of tests were undertaken. If the changes in lengths at different points of the welded-in plug 2 B and 4 B are followed during a gradual increase in load, one finds a peculiar behaviour, particularly in those points which are immediately above the weld, as for instance, point 6 in Fig. 4 and points 5 and 13 in Figs. 5 and 6. Not only are the extensions at these points unexpectedly small even up to stresses of $\sigma_r = P/F = 26$ kg. per sq. mm., but they also show already for a relatively small average stress of $\sigma_r = P/F = 5$ kg. per sq. mm., a deviation from the straight line stress-strain relationship[8]. This deviation, however, from the straight line cannot be an indication of plastic deformation on top of the weld, which was shown by the measurement of the elastic recovery after cutting out the strain gauges 5 and 13 in the plug weld 4 B in which, as has already been mentioned, the fatigue fracture did not occur in the weld but at some considerable distance in the vicinity of the enlarged ends. If one takes account of the observed strains

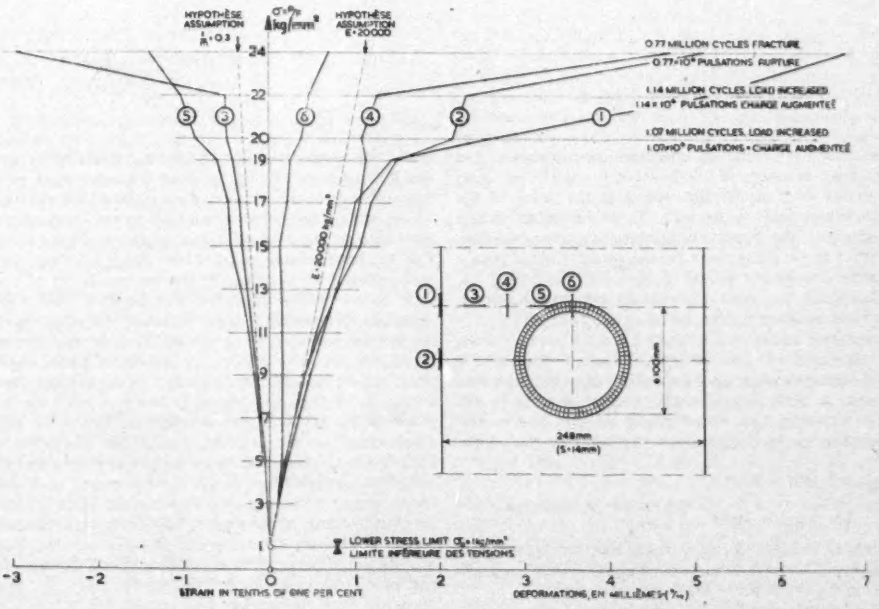


Fig. 4. Plug weld sécheron, second series, specimen 2B.

Measured strain from different limits of loading.

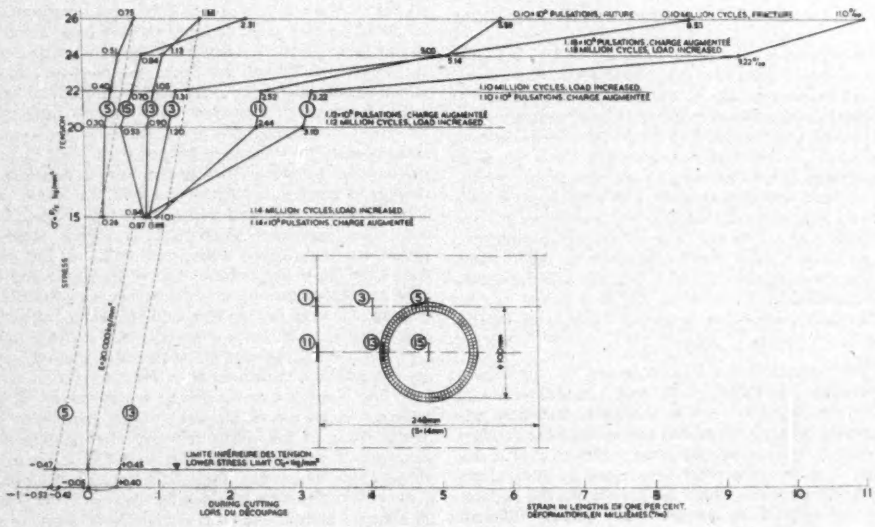


Fig. 5. Plug weld sécheron second series, specimen 4B.
Measured strain from different limits of loading.

during loading and unloading, one obtains at the point 5 a negative elastic recovery of 0·042—0·0005 = 0·037 per cent. for the steady state at the end, whilst at the point 13 the measured values add up to zero. These remanent strains would represent the pre-stress immediately after welding, that is, prior to the fatigue test on the assumption of purely elastic behaviour at the points of measurement 5 and 13, whilst the elastic recoveries observed during the subdivision gave the residual stresses after the fatigue test (Fig. 3).

The transverse strains at the points 5 and 13 have not been directly measured. If one assumes, however, that in the tangential direction of the weld the strain due to the pre-stress is the same at both points, namely, equal to zero in the transverse direction, one would obtain in this case in the condition prior to the fatigue test a pre-stress on top of the weld of

$$\frac{E \times \epsilon}{1-\frac{1}{m^2}} = \frac{21{,}000 \times 0{\cdot}37}{\left(1-\frac{1}{0{\cdot}32}\right) \times 1000} = 8{\cdot}5 \text{ kg. per sq. mm. tension.}$$

It appears to be an exceedingly small value for this point 5. Since, however, the total deformations at the points 5 and 13:

$\epsilon_5 = 0{\cdot}042 + 0{\cdot}075 = 0{\cdot}117$ per cent., and

$\epsilon_{13} = 0{\cdot}005 + 0{\cdot}168 = 0{\cdot}173$ per cent.

appear too small to be indicative of stresses reaching the elastic limit of the weld metal, which was shown to be 36 kg. per sq. mm., and since, moreover, a necking extension could not be observed during the fatigue test which preceded the measurement of the residual stresses, proof of which must be seen in the fact that the strains at the points 5 and 13 did remain the same during loading and unloading within the limits of accuracy of measurement, it must be assumed that the hyper-elastic deformation which has been observed early, must have occurred in the internal layers of the plug weld or else in the transition zone between weld and plate material. In addition it must be taken into account that in the present cases of V- or double V-welds, the diameter of the transition zone is not constant for different depths. It need not be assumed as a matter of course that the first exceeding of the elastic limit in the test must have taken place at the point of measurement or below the point of measurement in the interior. The points where the elastic limit is first exceeded must be sought at points which have not been explored by direct measurement. This example shows clearly how very careful one must be in drawing the conclusion that hyper-elastic behaviour or relaxation is taking place from observing non-linearity between load and extension (not perhaps stress and strain) at a definite measuring point, because of the possibility that the observed deviation from the straight line relationship between P and ϵ—load and strain—may be caused by hyper-elastic behaviour of other parts of the test piece which cannot even be explored by measurement.

Measured strain from different limits of loading.

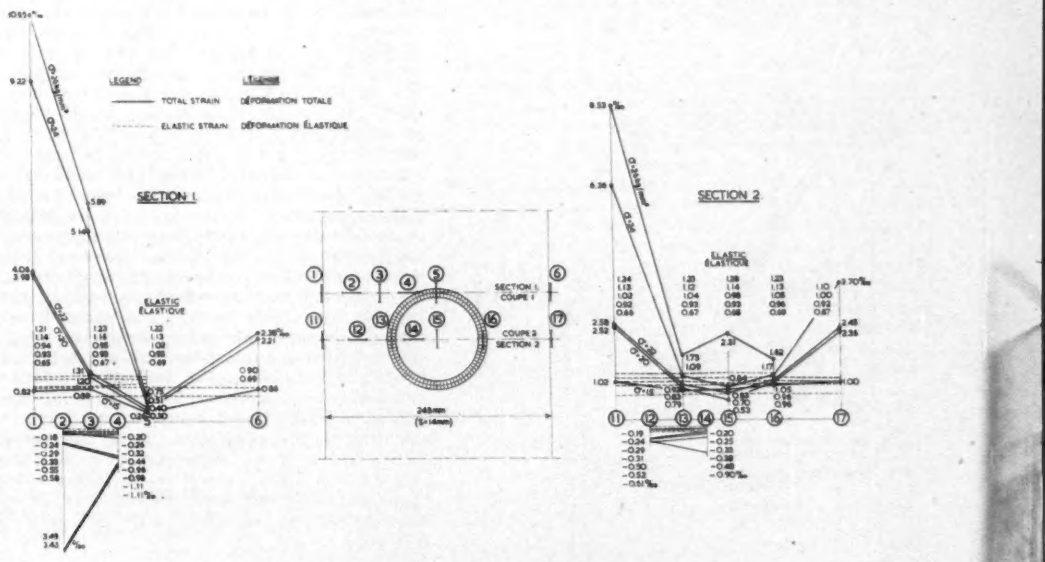


Fig. 6. Plug weld sécheron, second series, specimen 4B.

Measured strain distribution in the cross-section for limits of loading 15, 20, 22, 24 and 26 kg. per sq. mm. and lower stress limit of 1 kg. per sq. mm. (The plotted points are the mean between measurements on both sides.)

6. FLAT SPECIMENS WITH AND WITHOUT SINGLE WELD BEADS DEPOSITED ON ONE OF THE EDGES OF THE SPECIMEN

This investigation comprised a total of eight test pieces with unmachined surfaces which were strongly pitted because it was material which had been in stock for some time. Of these, two test pieces were not welded and not heat treated, two test pieces were welded and low temperature annealed (stress relieved), two test pieces were welded and not low temperature annealed and two test pieces were welded and low temperature annealed.

The material exhibited the following properties:—

Limit of Proportionality ..	σ_P	= 20·0 kg. per sq. mm.
Upper Yield Point	σ_{So}	= 22·7 kg. per sq. mm.
Ultimate Tensile Strength ..	β_z	= 34·2 kg. per sq. mm.
Reduction of Area	ϕ	= 75·0 per cent.

The low temperature annealing had only an insignificant effect on these properties:—

Limit of Proportionality ..	σ_P	= 22·9 kg. per sq. mm.
Upper Yield Point	σ_{So}	= 22·9 kg. per sq. mm.
Ultimate Tensile Strength ..	β_z	= 36·8 kg. per sq. mm.
Reduction of Area	ϕ	= 70·0 per cent.

The material was mild steel of good toughness with a relatively low yield point. The basic tensile fatigue strength of the material was

$_e\sigma\,\delta$ = 23·4 kg. per sq. mm. for the material with mill scale, and

$_e\sigma\,\delta$ = 33·7 kg. per sq. mm. for the material machined all over.

According to these figures the surface pitting reduces the basic tensile fatigue strength of unwelded mild steel by 10 kg. per sq. mm., which is a reduction to the same value as that obtained for good welds with machined surfaces. The following basic tensile fatigue strength values were obtained for 1,000,000 loading cycles with these eight specimens of 90 by 12 mm. cross section:—

	$_e\sigma\,\delta$ *in kg. per sq. mm.*
Unwelded, not heat treated	23·4 and 24·0
Unwelded, heat treated	21·2 and 21·3
Welded, not heat treated	20·0 and 23·1
Welded, heat treated	20·0 and 19·9

It follows from these figures that the heat treatment results rather in a reduction of the fatigue strength of the unwelded as well as the welded test pieces.

In order to determine the residual stresses in the welded and not heat treated test pieces, a separate test piece was used which had not been subjected to any loading. The electric resistance strain gauges SR 4 which had been attached to the test piece, showed strains after being cut out, which are reproduced in Fig. 7. The maximum value of the tensile stress in the weld was 14 kg. per sq. mm. Since in all the above cases, with the exception of that which has been marked with an asterisk where the fatigue fracture started from a surface defect, the origin of the fatigue fracture was located in the weld, it is proved that mono-axial residual stresses in faultless welded connections up to a magnitude of 14 kg. per sq. mm. in the initial condition, that is, prior

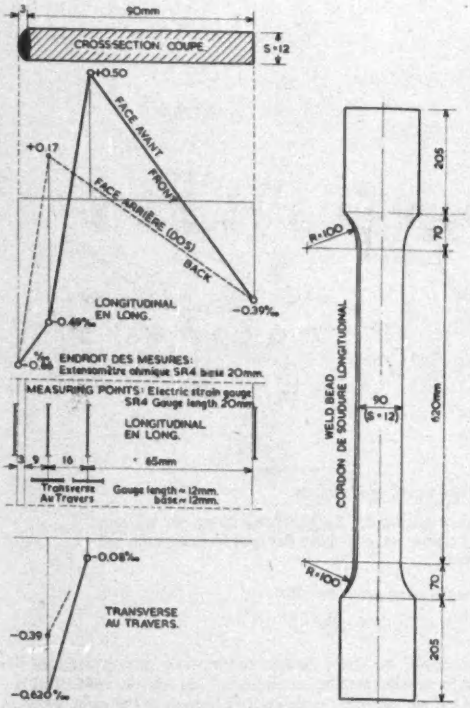


Fig. 7. Flat specimen with weld bead deposited along one edge. Not stress relieved. Measured strain during cutting.

to the fatigue test, do not exercise a deleterious influence on fatigue strength. The reason why the residual stresses are relatively low is that the surrounds of the weld bead could reach a high temperature because they are surrounded by little material. This is shown also by the relatively wide heat affected zone as shown in Fig. 7. A weld bead on the surface of the plate or any re-entrant corner would have had high residual stresses as a consequence. It has to be pointed out, however, that the residual stresses measured by cutting out pieces of material to which strain gauges have been attached, merely give the average values for a relatively large gauge length of the true residual stresses, so that the latter can be considerably larger purely locally.

In judging the influence of residual stresses on the fatigue strength a particular circumstance of the determination of the residual stresses has to be pointed out, which, as far as we know, has not sufficiently been taken into account. If the residual stresses are to be determined from the measured strains with the aid of the modulus of elasticity E and Poisson's ratio m even approximately, it must be supposed that the measured spring-back is purely elastic, that is, the deformation in the whole of the test piece must be free of hysteresis and Bauschinger effect and free of all plastic deformation during the cutting of the measuring points. It is much more difficult to satisfy these requirements than appears at first sight. If, for instance, a piece of material is pre-stressed with a stress which is half the yield point it is sufficient to drill a hole in this material in order to produce Lüders lines at the edge of the hole. Thus plastic deformations produce new residual stresses in the piece of material and without knowing these it is impossible to determine the residual stresses which have been present originally. It is not even necessary for the yielding to occur within the gauge length of one of the strain gauges. Equally dangerous can be the execution of saw cuts without any particular plan, in as far as the results of the measurements depend to a very large degree on the sequence of making the holes or of making the cuts, and this requires special study. That very little attention has been paid to this fact so far becomes evident in that sometimes the residual stress distributions which have been determined exhibit a quite unexpected appearance and are apparently far from equilibrium. One has expressed the view that in such cases the residual stresses in the interior are different from those measured on the surface with respect to their magnitude and their tri-axiality σ_1, σ_2 and σ_3. This, however, need not necessarily be the only cause of these deviations.

7. WHAT CONCLUSIONS CAN BE DRAWN FROM THE ABOVE INVESTIGATIONS ON THE INFLUENCE OF RESIDUAL STRESSES ON FATIGUE STRENGTH

As is well known it has so far been impossible to arrive at a unanimous view on this question in engineering circles. Many of the set-backs which have occurred during recent years, especially in welded structures, have been attributed to residual stresses and in particular to tri-axial residual stresses. In opposition to this, the Federal Institute for Testing Materials in Zurich has taken the view already in 1941, on the basic of many years of experience, that normally the additional internal stresses are practically without any influence, provided that structural discontinuities in the form of fine cracks are absent and provided that the ability of the structural steel is sufficient to reduce stress concentrations in good time. For this purpose a few tenths of a per cent. of plastic deformation are sufficient, and this deformation as a rule is sustained by faultless material without causing premature fatigue failure.

Welding assumes a particular position because here material and structural factors occur combined with mechanical and thermal influences. The question is posed whether one can say anything on the influence of the additional residual stresses which occur in welded connections on the basis of the present tests.

This question can be answered reliably only for welded connections of first-class quality of the second series of tests Sécheron. These tests comprise welded-in plugs in narrow and wide test pieces which have not been treated in any way after welding and for which, however, any influence of residual stresses, which would have to be assumed to increase in magnitude with increasing width of specimen, has not been found. Accordingly, the residual stresses appear to be without influence in this region. When, however, small test

pieces were cut out of the plug welded specimens, a somewhat higher basic tensile fatigue strength was found for these, namely:—

	Basic Tensile Fatigue Strength kg. per sq. mm.
Welded-in plug	24
Small test pieces cut from plug specimens	26
Test pieces from plate material ..	29
Test pieces from the weld alone ..	40

The specimens with welded-in plugs, therefore, did not quite reach the fatigue strength of the plate material, which is that part of the test piece which exhibits the lowest fatigue strength. The difference between the fatigue strength of the plug specimens as a whole and the test pieces which were cut out from the weld (24 as compared with 26 kg. per sq. mm.) may be partly due to the multi-axial residual stresses and the non-uniform stress distribution over the cross section, and partly due to the fact that the weakest point of the connection is more likely to be contained in the whole test piece than in the narrow test pieces taken from arbitrarily chosen points in the whole plug welded connection. The difference of 2 kg. per sq. mm. (8 per cent.) might be explained by this circumstance.

It is much more difficult to find an explanation for the fact that the small test pieces, cut from the whole plug welded connection and containing the weld, did not reach the fatigue strength of the machined plate material (26 as compared with 29 kg. per sq. mm.). For this one can put forward only one explanation, namely that in the transition zone from weld metal to plate material a thin layer of the plate material is molten which, after solidification has the properties of a cast steel of the same composition as that of the previous rolled steel. There may be an additional influence from small flaws such as unavoidable lack of fusion and differences in structure as well as residual stresses in the transition zone. If this interpretation of the test results is not accepted one could speak of an influence of residual stresses of approximately 8 per cent., that is 24 instead of 26 kg. per sq. mm., on the basis of the second series of tests Sécheron. Such influence, however, should have become fully evident already in the small welded-in plugs and even in welds with extraordinarily high residual stresses equal to the yield point of the material. This is not in any way sufficient to explain the mishaps previously mentioned which have occurred during recent years in welded bridges and welded ships.

These expositions, however, were valid only for the case of welds Sécheron second series of first-class quality. Less conclusive are the preliminary tests with welded-in plugs which, despite relatively small flaws, which when X-rayed would have permitted the weld to be designated as almost completely faultless, resulted in considerably lower fatigue strength values ($_{o}\sigma_{\delta} = 17$ kg. per sq. mm., fracture after 450,000 cycles). It may be assumed that small test pieces taken from this welded-in plug connection would have exhibited higher fatigue strength values, so that for faulty welds a noticeable influence of the multi-axial residual stresses on fatigue strength would have to be considered possible. It would be desirable to examine this question in more detail by means of more extensive series of tests carried out on welds of different quality. For the present it is possible to take responsibility for ignoring the influence of residual stresses only in the case of good welds. This should be an incentive for first-class quality welding with machined surfaces, or at least with machined zones of undercut, especially in the case of structures and parts of machines which are subjected to many repetitions of loading.

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R.62

A Review of Recently Published Information on the Spot Welding of Light Alloys

(With particular referenee to Stored Energy Methods)

By P. M. TEANBY.

This Report was first issued to Members of B.W.R.A. as a confidential report in May 1950

1. INTRODUCTION

The purpose of this review is to provide a summary of existing information on spot welding. A brief summary of the types of spot welding machines that are in present use is included. This is followed by a review of information on the variables of welding machines and their effect on the production of good welds.

A section on surface preparation prior to welding is also included.

2. MACHINES

There are four main types of machines which are or have been used for the spot welding of light alloys.

(*a*) The conventional a.c. equipment.
(*b*) The capacity stored energy type.
(*c*) The magnetic stored energy type.
(*d*) The battery stored energy type.

Apart from (*a*) all these machines use methods of stored energy. This has the advantage of distributing the welding electrical load over a comparatively long period of time. Coupled with the use of three phase supply, this enables welding machines of a high capacity to be operated on normal power circuits and at the same time reduces supply disturbances to other consumers.

Type (*b*)

In the capacity stored energy type a bank of condensers are charged through a three-phase rectifier at a predetermined voltage, the capacity being variable by altering the number of condensers in circuit. On initiation of the weld the charging circuit is broken and the condensers are discharged through the primary of the welding transformer inducing a high current in the secondary circuit for a short space of time.

Type (*c*)

The magnetic stored energy equipment is also normally supplied through a three-phase rectifier. The direct current is used to build up an intense magnetic field in a specially designed transformer. When this current is interrupted the rapid collapse of the magnetic field momentarily induces a high current in the secondary circuit. (See Fig. 1.)

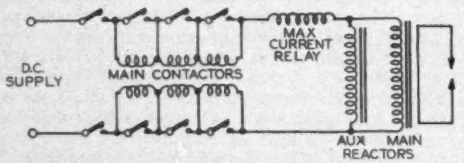

Fig. 1. Schematic diagram of magnetic spot welder.

Type (*d*)

The battery stored energy type, which has been developed in America, is similar in appearance to the conventional a.c. type resistance welding machine. The essential difference is that a bank of storage battery cells replace the customary welding transformer. Control equipment for battery welders such as timers, "heat" regulators, and contactors are simpler than those of other types of stored energy machines. The welding capacity can be extended merely by increasing the number of cells in circuit. Welding rates depend primarily upon the output capacity of the battery charger employed. Such equipment has been successfully used to weld up to 3/16 in. by 2 in. aluminium sections.[1]

A typical battery-powered installation is shown in Fig. 2.

Since this review was written, details of two further systems of electrical energy supply have been published. These are the Kinetic stored energy type and the three-phase system which are reviewed in Appendices A and B.

3. LOAD CYCLE CHARACTERISTICS

The term load cycle is used to describe the variation in mechanical load which occurs during the period commencing with the closing of the electrodes on the workpiece and completed by raising of the head after welding has occurred.

Electrodes are required not only to provide a means of concentrating the welding current, but also to ensure adequate consolidation of the weld. The electrode system must provide sufficient restraining force to prevent metal from splashing between the sheets during welding and, during the cooling of the weld must provide a consolidating force to eliminate weld porosity and cracking. This means that the moving electrode must follow closely the cooling and shrinking weld; the moving electrode system must therefore be of low inertia with minimum friction.

There are two major types of electrode load cycle used in the spot welding of light alloys, firstly the constant load cycle in which the electrode load remains constant during and after the flow of the welding current until the welding head is raised, and secondly, the variable load or "forge" cycle in which a rapid increase in load occurs after the current flow, the time at which the load increases being controlled in relation to the current peak. Load cycles are defined as follows:—

1. Welding Load—the electrode load at which the welding current flows.
2. Forge or Final Load—the maximum consolidation load applied after the current flow and measured only in variable load cycles.
3. Forge Delay—the time interval between the start of the current rise to peak and the start of the load rise from weld to forge. It is sometimes taken on the time interval between peak and forge peak.
4. Mean Rate of Forge Increase—which is measured as the difference in maximum load and welding load divided by the time for load to increase from weld to forge.

Fig. 3 illustrates various types of load cycle. The importance of the load cycle in affecting the quality of a weld is indicated in the following brief account of the cracking problem in duralumin type light alloy spot welds.

"The most frequent type of cracks observed radiate from the centre of the weld in planes perpendicular to the surface of the sheet, and the extreme case may be visible at the surface. These cracks appear to arise from shrinkage stresses imposed on the weld during cooling. When the current pulse flows, the metal in the vicinity of the electrode expands through heat expansion against the restraining effect of the surrounding cool metal and the force of the electrodes. Some plastic flow of metal is inevitable, particularly when the weld is formed and is in a molten or plastic condition. The weld solidifies and contracts during cooling against the restraining force of the surrounding metal, thus inducing shrinkage stresses which may be of sufficient magnitude to produce cracking."

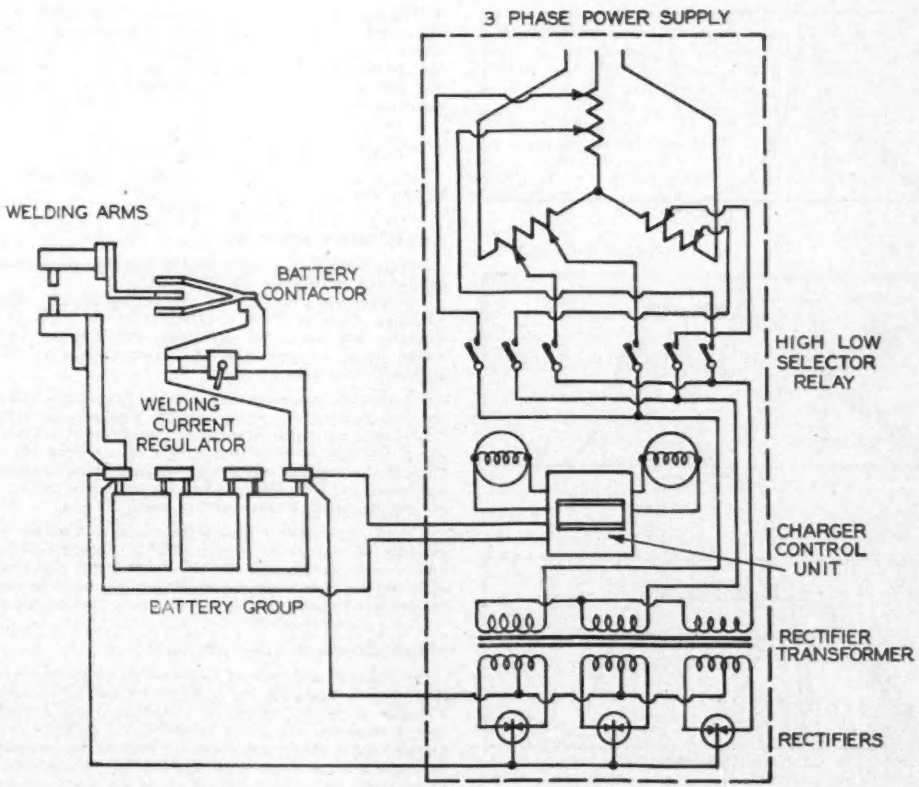

Fig. 2. Schematic diagram of battery operated spot welder.

It may be possible to reduce shrinkage stresses by plastic deformation of the metal during cooling, effectively counteracting the tendency for cracks to form, and reducing residual stresses after welding. This can be undertaken conveniently by means of the electrode load cycle.

The constant load and variable or forge load cycles when properly adjusted, should be capable of eliminating cracking. The former cycle will require an electrode welding load of sufficient magnitude to produce the desired deformation and the latter cycle will require a forge load of correct magnitude, the time of application being accurately controlled in relation to the current peak. Small welds will be obtained if it is applied too early, e.g., when the current peak is reached, and there will be insufficient plastic deformation if the weld has appreciably cooled, i.e., if the delay has been too long.

The use of the constant load cycle has not yet been favoured by machine manufacturers in light alloy welding in spite of its relative simplicity, the reason for this being found in the electrode load at which the current flows in each type of cycle. The constant load cycle will require a very high welding current load to eliminate cracking with consequent inordinately high welding current demand, the energy required for welding increasing with increase in electrode welding load. The forge cycle will require less energy since the welding load may be relatively low and consolidation can be effected by the forge load after the passage of the greater part of the welding current.

4. CURRENT WAVE SHAPE

The fundamental difference between welds made with a rapidly rising current wave form and those of a slowly rising current appears to be in the manner in which the weld evolves.

A slowly rising current concentrates at a single spot which grows in size as the current increases. A rapidly rising current is conducted across the sheet to sheet contact at a great many small spots which may be well distributed over the entire contact area or concentrated in a ring pattern near the periphery of the contact area. If the initial surface breakdown occurs largely at the periphery, it is possible that the weld will be annular in shape.[4]

When the slope of the wave form is very gradual and the surface resistance is at its proper low value, the initial breakdown of the remaining surface film will take place at the centre of the weld rather than at the periphery which occurs when a steep wave form is used. This suggests that the best wave form would be one which tended to produce an initial breakdown uniformly over the weld area. The steeper wave form tends to give rise to a more flat strength current characteristic which should be advantageous in operation.

The impression is thus obtained that the welds should be made with the steepest wave form consistent with avoidance of annular welds and flashing. The permissible steepness will vary with the thickness of material welded.

The investigators under review are of the opinion that current wave and pressure cycle are closely interwoven. There appears to

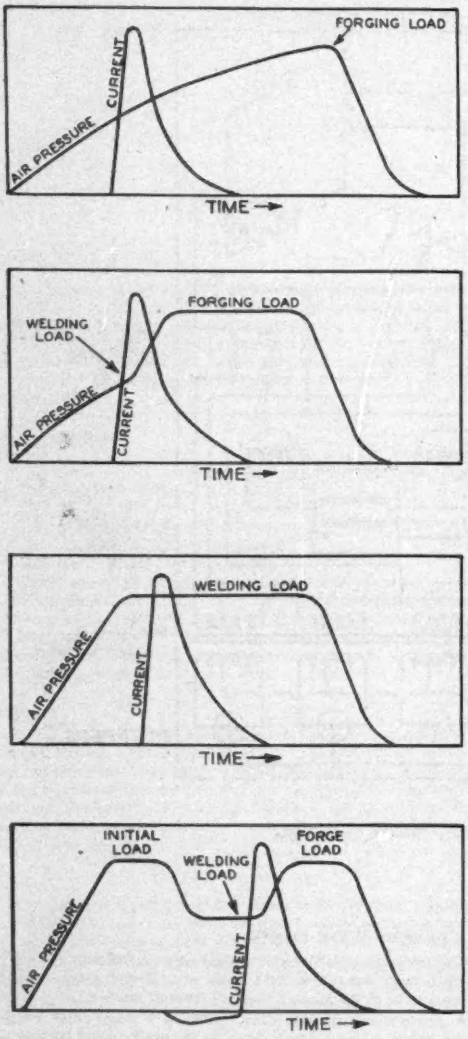

Fig. 3. Types of variable and constant load cycles.

be an optimum combination of wave form and pressure cycle which gives the widest range of current between the incipient weld region and the region in which fine cracks, sheet separation and expulsion are likely to occur.[4]

From the metallurgical point of view the wave form employed does not affect the weld nugget structure.

Another objectionable effect of too steep a wave form is flashing between the sheets and occasionally beneath the tips of the welding machine electrodes. When this condition occurs the steepness of the wave form is reduced by increasing the turns ratio of the welding transformer. When this is done it is necessary to make adjustments in the case of capacitance type machines to the condenser or capacitance and condenser voltage. In this type of machine the wave shape is determined by supply voltage, capacitance and turns ratio[6] each interdependent on the other two. (See Figs. 4 to 6.)

5. ELECTRODE STRIKING VELOCITY

There is no literature available relating in detail to Electrode Striking Velocity.

6. ELECTRODE SCUFFING

Surface skidding is an effect usually indicative of electrode tip misalignment or electrode arm deflection.[8]

The upper and lower arms of spot welding machines must be sufficiently rigid to minimise deflection of the electrode tips. Excessive deflection causes inconsistent spot strengths, irregular shaped welds, expulsion, cracking, excessive pick up and misalignment of parts being welded.[7]

The electrode stakes are often a source of excessive deflection, and it is necessary to ensure that the electrodes are carefully bedded in to the tapers to ensure no possibility of deflection by tilting. The high pressures used in light alloy welding call for a much greater degree of care in machining and fitting of electrodes and stakes, and provision for taking the loads from locking bolts of large machined surfaces should be made.

A result of electrode scuffing is the reduction of the life of the electrode tips caused by pick-up. This is a mechanical action similar to the loading of a file with a soft metal. This action is much more apparent with the upper electrode which appears to require more frequent dressing or replacement than the lower.[10]

7. VARIATIONS IN LINE VOLTAGE

The effect of small voltage variations on contactor operation appears to be negligible, but variations in line voltage produce variations in rectifier voltage for condenser discharge machines and, if excessive, will give a noticeable inconsistency in weld strengths due to the variable energy supplied to the condenser. It was found that a mealtime break caused the line voltage to increase 10 to 15 volts on a normal 400 volt circuit which was sufficient to make an adjustment necessary to correct the weld energy. In this case the machine was connected to a comparatively small power sub-station and considerable voltage fluctuations were noticeable due to load changes.

8. VARIATIONS IN LINE PRESSURE

No information was found on line pressure variations, but it is apparent that if variations of considerable magnitude should occur, the effect on the weld and forging pressures might be proportional, depending upon the efficiency of the reducing valve. This no doubt would cause many of the effects similar to an original maladjustment of the pressure valves such as cracking, sheet separation and high contact resistance.

Small variations in the air line supply are frequently compensated by the use of a pressure tank in series with the air line at a point somewhere near the welding head. This provides a reservoir of pressure in the event of sudden heavy demands.

9. ELECTRODE MATERIALS

The main requirements of an electrode material for light alloy spot welding are high electrical conductivity, high mechanical strength, high recrystallisation temperature and minimum tendency to alloy with the material being welded. From the practical point of view the best material is that which gives the longest life between machinings with minimum tip dressing and minimum thermal disturbance to the surface of the material being welded. In practice it is necessarily a compromise between the requirement of high electrical conductivity and that for minimum tip mushrooming.

It is generally agreed that the electrical conductivity should not be less than 85 per cent. of the I.A.C.S. standard, and it is not surprising that high conductivity electrolytic copper is widely used in this country. Its recrystallisation temperature is sufficiently

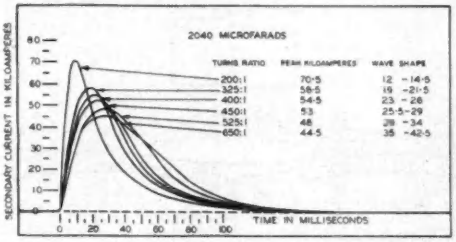

Fig. 4. Variations of peak secondary current and wave shape with increasing turns ratio 2040μF, 2000 v. Wave length and peak current is fowered with increase in turns ratio.

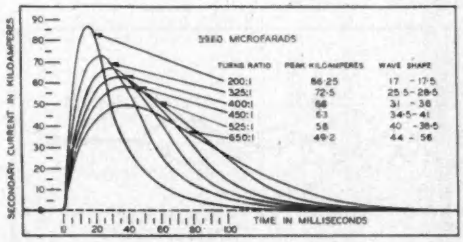

Fig. 5. Variations of peak secondary, current and wave shape with increasing turns ratio 3960μF, 2000 v. Added capacitance raises peak and lengthens wave in comparison.

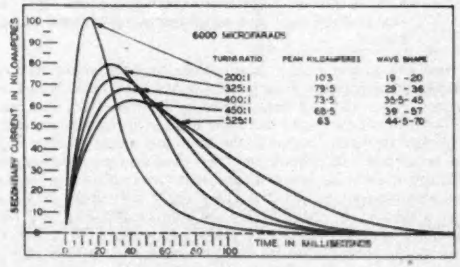

Fig. 6. 6000μF, 2000 v.

low, however, for the local heating at the tip to cause appreciable softening after a short time with consequent "mushrooming" and necessitating relatively frequent re-machining. The use of copper with small additions of alloying elements to raise recrystallisation temperature is thus increasing. The further effect of these additions is a reduction of electrical conductivity and in some cases an increase in the electrode pick-up characteristics, and these latter conditions limit the extent of the alloying additions.

The additions generally used in this country are nickel-tellurium and occasionally cadmium (1 per cent.). Copper with small additions of silver, nickel, cobalt or chromium has also been used, and several good proprietary alloys are available.

It is interesting to note that copper-chromium alloys, such as are commonly used for steel welding, are rarely used in this country because of increased electrode pick-up, but have been frequently used with success in America. The reason for this general difference in experience is to be found in a consideration of the practical welding conditions. American practice is to make relatively large welds with high tip loads, conditions under which hard drawn electrolytic copper readily mushrooms. In this country the use of hard drawn H.C.E. copper is generally satisfactory where low electrode loads are in use, and the service conditions of the electrode are not severe.

10. EFFECT OF BAD FITS

Hard metal, especially if it is springy, causes trouble in obtaining the necessary intimate contact of the sheets, and a variety of conditions as shown by Studer[16] which may result in considerable variations in surface contact resistance.

Springy sheets are likely to be particularly troublesome when using a machine with variable pressure cycles in which pressure is reduced when welding current flows. (See Fig. 7.) Another mechanical aspect of this is the desirability of accuracy of production of pressings and formed sections to be joined by the process. The surface should meet without relying on electrode pressure to make up for poor pressing technique.

Studer[16] points out that if two metal surfaces of ordinary finish are pressed into contact they will, in general, touch initially at very few points. As the force is increased, these points will yield, first elastically, then plastically, and new points will come into contact. This will continue until there is enough total area to balance the force without further yielding. When this condition occurs, the probable situation at the boundary is that indicated in Fig. 8 with the following types of contact areas:—

1. Region A, where the yield point of the material has been passed, and the surface films have been ruptured so that there is intimate metallic contact.
2. Region C, where the surrace films of the two surfaces are pressed together, but in such a way that they remain iritact, and maintain a thickness of a fairly large number of molecules.
3. Region B, where the yield point of the metal has been exceeded, and the molecules of surface films have been pressed into and mingled with the metal, producing an area of poor conductivity, as compared with the A regions, yet good with respect to the unruptured films.
4. Regions D, which are pressed together, but when the elastic limit of the metal has not yet been reached. Here again the surface film may be ruptured or left intact. The conductivity characteristics will be the same as areas of types.
5. Region E, where there is an actual air layer (many molecules thick) between the samples, not all types of contact need, of course, be present in any given case.

11. THE EFFECT OF SURFACE PREPARATION ON STRENGTH AND CONSISTENCY

The pre-welding surface preparation of light alloys is an essential requirement for the production of welds of high quality, in particular, welds of high strength consistency and good appearance. The process may be divided into two parts. Firstly, the removal of surface grease, paint, dirt or dye identification marks, etc., and secondly the removal of the surface oxide film. The reason for this cleaning is to be found in the variable high resistance of the natural surface oxide film which can give rise to undesirable electrode pick-up, surface burning and variable heat development at the sheet to sheet interface.

Surface condition is probably the most important factor affecting weld strength consistency and the cleaning techniques used must be capable of producing uniform low surface resistance on a given job, and from one job to another. Since the heat developed at the interface for a given current is determined by the interfacial resistance it has been concluded by some authorities that a high resistance may be tolerated at the interface to obtain stronger welds for less energy output. Rajakovics and Blohm[11] describe experiments in which only the sides of the material which came

into contact with the electrode tips were cleaned. It should be emphasised, however, that it is not possible by this means to obtain welds of the same strength consistency as given by a low and uniform interfacial resistance. This aspect has been emphasised by Hess and co-workers[18 27] and other authors.[8] A high interfacial resistance will always break down irregularly, particularly if the wave front of the secondary current is steep. It is obvious that for some types of machine employing inherently steep wave fronts, i.e., condenser discharge and the reactance storage machine, it is impossible to obtain satisfactory welds without interfacial cleaning.

Hess and co-workers[15] have also indicated the importance of using welding conditions which are in themselves not critical in relation to the formation of the weld. This is explained by reference to what has been called the "strength characteristic curve."[28] If welds are made on the steep part of the curve, it is obvious that small variations in surface resistance, current, etc., can have a relatively large effect on the weld strength, in particular, the consistency of the weld will be poor. Similarly, if welds are made towards the peak of the curve, similar variations can have only a small effect so that strength consistency must be improved when working to this part of the curve. With alternating current machines it is possible that reasonable welds may be made by this means without interfacial cleaning, although the results must be inferior to those obtained when a proper cleaning sequence is used.

De-greasing

The use of trichlorethylene vapour baths for preliminary degreasing of aluminium alloy sheets is almost universal in this country and America. Very dirty sheets may receive hand treatment with liquid reagent for the removal of any paint marks which would not be completely removed in the vapour bath. Hot alkaline degreasers based on sodium carbonate, tri-sodium phosphate and sodium silicates are also widely used for final degreasing,[27 29]. These latter reagents not only remove surface grease but also have an action on the surface oxide film.

Removal of Oxide

Both mechanical and chemical methods have been used for the removal of surface oxide, either separately or together for particular applications. As a general rule, mechanical methods based on the use of a rotary scratch brush, have been used for small installations or laboratory research investigations where the necessary careful handling may be given. Chemical methods are used mainly for large-scale production installations because of their better suitability for handling large throughputs. Numerous reagents have been used and recommended in the past, but it is a safe conclusion that all reagents based on hydrofluoric acid and caustic soda are unsuitable for production cleaning because of the extremely critical time of treatment.

Modern developments have been towards the use of the reagents which are relatively non-critical in reaction and which may be used at room temperature, i.e., towards a reagent which may be used on a variety of materials and in which a considerable latitude is possible in time of treatment. It is not surprising then that solutions based on hydrofluo-silicic acid operated at room temperature have been widely adopted in recent years. Hess and co-workers[31] recommend a solution of 3 per cent. acid by volume for coated alloys, but Scott and Burr[30] have shown that a 1½ per cent. solution is to be preferred. The following reagents have been used and recommended by a committee of the British Welding Research Association:—

(*a*) Coated Alloys.

1. Hydrofluo-silicic acid[30 31] 7-10 grams per litre (total acidity as sulphuric acid: 50-100 grams per litre).
2. Phosphoric acid solution[5] (5-10 per cent. by volume at 120 deg. F. with wetting agent).
3. Sodium fluoride-sulphuric acid solution (1 per cent. by weight sodium fluoride, 10 per cent. by volume concentrated sulphuric acid). This bath is operated at room temperature but is not usually as satisfactory as solutions (1) or (2).

(*b*) Bare Alloys.

1. Phosphoric acid solution as given above followed by a flash dip in nitric acid solution to remove the black smut produced on the surface by the phosphoric acid.

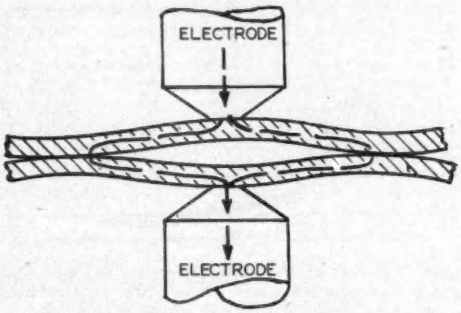

Fig. 7. Schematic sketch showing path of current when sheets are too springy or ill-fitting.

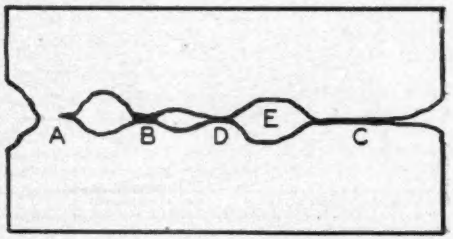

Fig. 8. Illustrating the various types of contact area.

2. Wire brushing after treatment in above chemical solutions. A brush of 4 in. diameter is recommended with 40 s.w.g. wire and operated at a peripheral speed of 3,000 ft. per minute.

Hess and co-workers[27 31] have pointed out the importance of distinguishing between material which has been heat treated in an air furnace and that heat treated in a nitrate bath. Air heat treated material responds much more quickly to chemical methods of surface treatment, although the same low values of resistance can be obtained in either case. They have also reported on the difficulty of obtaining low and consistent surface resistance for the very thin gauges, i.e., material about 0·020 in.[27] thick. This has been attributed to the diffusion of core constituents into the cladding. Material which has given poor results by chemical cleaning can generally be reclaimed by mechanical wire brushing, and this technique has often to be applied with very thin sheets. The cleaning of extruded sections and material which has received very heavy forming during manufacture is often a real difficulty, and this may be due to the use of lubricants during the processing operation and to consequent contamination during processing.

Washing of Chemically Treated Material

After any chemical process the specimens must be thoroughly washed to remove acid solution adhering to the surface. This is usually done by thorough swilling in cold running water. It is not usually convenient to dry the material immediately after cold washing by suspension in air and most installations have an additional bath in hot water to facilitate drying. If a final wash in hot water is given it is particularly important that the temperature should not exceed about 40 deg. C.,[14] otherwise rapid reoxidation of the cleaned surface will occur with a consequent increase in surface resistance. Further, if the main water supply contains lime,

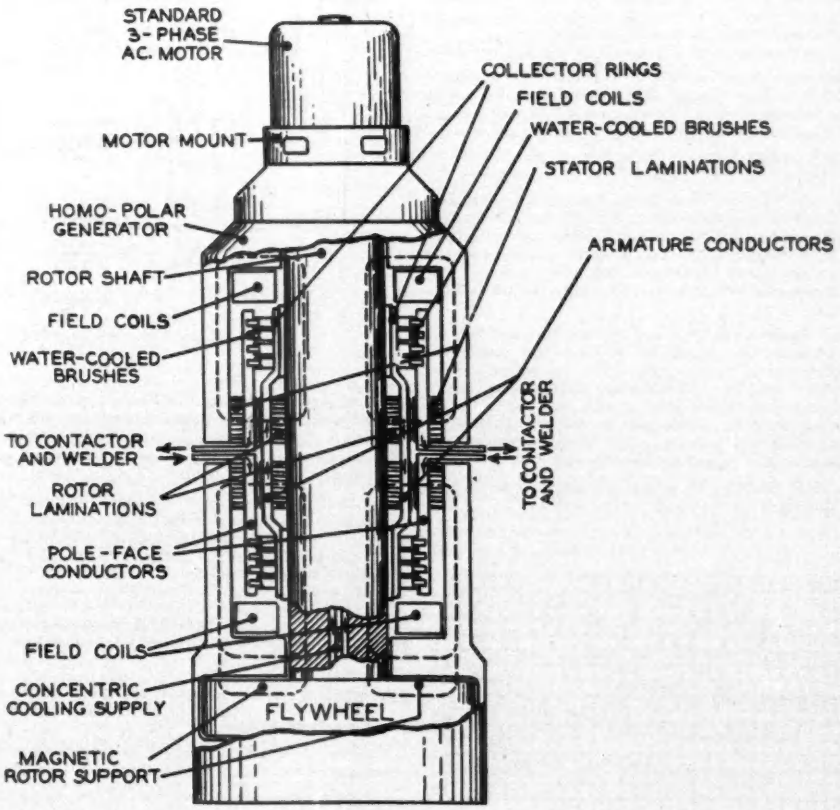

Fig. 9. Schematic cross-section view of motor-generator-flywheel unit.

an increase in resistance will certainly occur if this water is allowed to dry on the surface. The use of hot distilled water is recommended in such cases. Scott and Burr[30] favour drying in air without the use of a hot wash.

APPENDIX A

D.C. Resistance Welding Utilising Kinetic Energy Storage

A homopolar generator originally designed by Faraday has been used for this purpose. It consists of a copper disc which, when rotated between the poles of a horse-shoe magnet, develops a direct current between its centre and its periphery. This type of machine has a notoriously poor voltage regulation under load, due to armature reaction.

J. V. Capute invented improved methods of compensating such machines which permitted the design and construction of a unit rated at 7·5 V., 150,000 amp. continuous duty.

Due to the fact that the homopolar generator has effectively, only one armature conductor, the induced voltage for a given speed is determined by the number of lines of flux cut by this conductor each revolution. All of the flux must pass axially along the rotor core through the collector ring, and the diameter of the latter must be held down to keep brush velocities within a reasonable range. These considerations led to the design for a machine that was actually two generators back to back with their rotors joined axially and their armature conductors joined directly in series, so that their induced voltages were additive and each unit needed but half of the required machine voltage.

Referring to Fig. 9 it can be seen that the generator unit is symmetrical about a horizontal plane through its approximate centre. The dotted lines show the field flux linkage paths through each half of the unit and it should be understood that the direction of flux is opposite in the two ends of the motor so that there is no interaction between the two magnetic circuits and so that the polarities of the induced voltage make them additive.

Compensation by the Capute method previously mentioned is affected by bringing the brush loads out through the stator laminations. It will be seen that load current flowing in these conductors is opposite in direction to that flowing in the armature conductors located close to the air gap on the other side of it. So that the tendency of the current in the armature bars to rotate, distort, or collapse the field use, is substantially cancelled by the opposing action of the current in the stator pole-face bars. The use

of open slots for the conductors aids this action without changing the induced voltages.

Further, a compounding effect is obtained by skewing the rotor bars between the collector rings and the rotor laminations in such a direction that current flows partially around the rotor, and the consequent amperes turns aid the field excitation coils.

Voltage or "heat control" is obtained by the field excitation. Excitation current (about 1 k.w. max.) is obtained from a selenium rectifier fed by a small "Variac" type transformer having a wide continuous adjustment range. A direct current voltmeter indicates the open circuit output voltage for set up adjustment and record.

The initial supply employs a three-phase, 4-pole, 220-440 V., 60-cycle, 15-h.p., 1700 V.P.M. squirrel-cage induction motor.

Windage and frictional losses in the machine are about 2 to 3 k.w. The rest of the motor rating is available for welding load, and it should be noted that this load can be integrated substantially as a first power function rather than a square function, since the rating is not determined by thermal rating of the generator, but rather by horse-power capacity of the motor integrated over a fairly long interval.

By proper choice of motor size and characteristics, and flywheel size, a combination can be matched to almost any programme of spot, projection or flash welding within the voltage current capacity of the machine. This particular generator can supply somewhat more than 50,000 amp. at a terminal voltage under load at about 5·5 volts, the open circuit voltage being about 7·0 V. Since the output is direct current, throat area is of little consequence and heavy copper leads can be used.

The contactor employed to control the generator is the one previously developed for the storage battery welder.

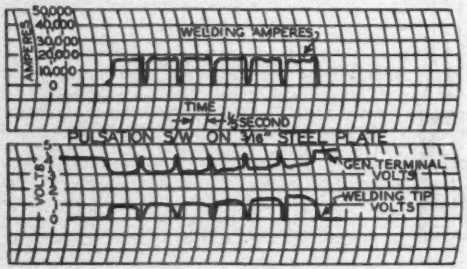

Fig. 10. Oscillogram of typical Pulsation spot weld. (Read from right to left.)

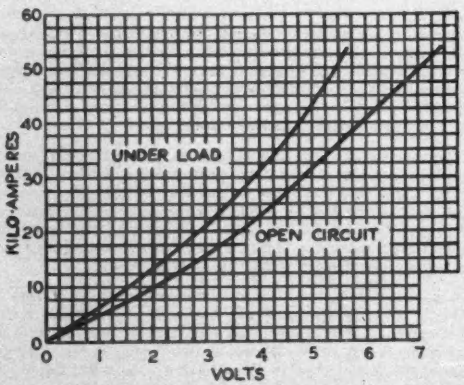

Fig. 11. Terminal voltage vs output (under load curves) with curve of comparable open cicuit voltage.

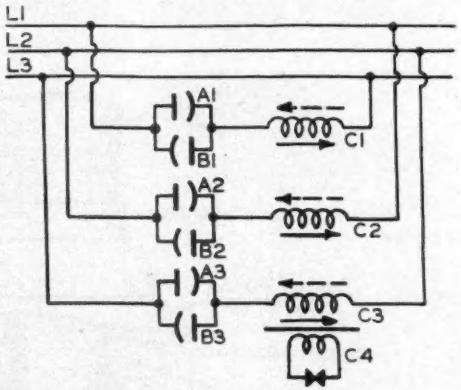

Fig. 12. Sciaky three-phase system.

Fig. 10 shows an oscillogram of a pulsation weld. Due to slowing of the flywheel the voltage declines during such a long weld interval but due to decrease in tip contact drop and probably contactor drop voltage as the carbons heat up the welding current remains quite close to a uniform value.

Fig. 11 shows the voltage short circuit current relationship. The curvature of the graph is probably due to non-linear characteristics of brush contact drop and the negative temperatures resistance characteristics of the carbon contactor. Fortunately, these effects are favourable to the purpose.

The system offers a very practical method for spot, multi-spot, projection or flash welding without requiring a power supply any heavier than that ordinarily used for machine tools.

APPENDIX B

The Three-Phase System

A further development, which it is claimed has considerable advantages for the welding of light alloys, is the three-phase system.

The operation of this system involves the passage of current in the same direction through three groups of coils which are wound on the same core. (See Fig. 12.)

In operation, tubes A1, A2 and A3 are made conductive first. Current will therefore flow from, in the case of A1, line 1 to line 3 passing through primary coil 1 in the process. The use of anode voltage causes A2 to operate and similarly A3 is caused to operate in turn.

The current through each group of coils being always in the same direction will produce magnetic flux in the core in the same direction. The increase in flux generates across the secondary an electromotive force which causes a heavy flow of direct current through the secondary circuit.

The current, which rises exponentially, can be set for a time corresponding to one to twelve cycles, depending upon the material to be welded before saturation is reached in the iron core. At the end of the desired impulse time, tubes A1, 2 and 3 are made non-conductive, and tubes B1, 2 and 3 are made conductive in a similar sequence.

Since the current is now flowing in the opposite direction through coils C1, 2 and 3, the magnetic flux is built up in the opposite direction to the previous firing and the voltage generated on the secondary will be in the opposite direction, thus creating a flow of current in the secondary circuit opposite to the previous impulse of current.

It is claimed that power demand to perform a specific welding job is lowered substantially, the line current on each of the three lines supplying a three-phase welder are identical, which produces uniform heating effects on all three lines and on all three phases

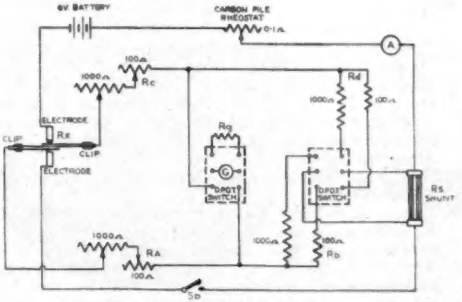

Fig. 13. The Kelvin double bridge.

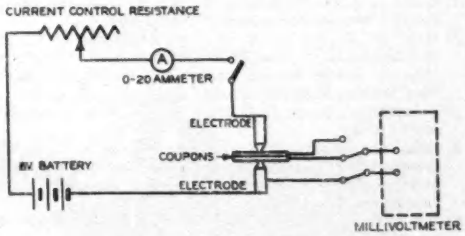

Fig. 14.

of the distribution transformers and systems. Furthermore there is no high current transient at the start of each impulse as when using non-synchronous control equipment on three phases.

The wave shape of the secondary current delivered by these machines has been found beneficial in the welding of aluminium. The slow rise of the secondary current during the welding period allows suitable contact between the tip and material to be established before the high peak secondary welding current passes through the material. Because of the uniform current density across the face of the tip, localised hot spots are not present to cause transfer of the material to the electrode, thus minimising the tip pick-up. Another feature to bear in mind is that the reversal of current tends to increase the number of spots that may be made before excessive pick-up or sticking to the electrode results.

APPENDIX C

The Kelvin Double Bridge for Measuring Surface Resistance of Aluminium Alloys

The apparatus consists of two basic parts, namely, a press and a bridge.

In operation two aluminium coupons are clamped between the electrodes and a pressure of 1100 lb. applied by the hydraulic jack. The alligator clips are fastened to each coupon.

To avoid reversed polarity the clips should be marked upper and lower. The galvanometer switch should be in the down position (see Fig. 13). The main switch Sb is pressed for an instant and the galvanometer will deflect violently. Immediately change the galvanometer switch to the "up" position and the clamping resistance rapidly returns the indicating beam to its next position. It will be well to keep the resistance Rg across the galvanometer at all times except when actually taking readings. When the switch is depressed a current of 50-75 amp. flows through the external circuit (heavy line), but very little flows through the measuring circuit due to its high resistance. The decade resistances are adjusted until the galvanometer no longer shows any deflection when the key is depressed. When the DPDT switch connects the 100 ohm fixed resistance in the bridge the decade box reading gives direct value in microhms. When the 1,000 ohm fixed resistances are used, it is necessary to divide by ton.

A method recommended by a previous British Welding Research Association Committee for contact resistance measurements consists of an ammeter with a range of 0 to 20 amps., a millivoltmeter with a full-scale reading of 3 millivolts. A 6-volt battery and some form of press with calibrated pressure settings (see Fig. 14).

The principal of one method which is considered suitable is to place two sheets of the test material between the electrode and to apply a load of 1000 lb. A known current is then passed between the electrodes by means of the battery. The potential difference between the two test pieces is then measured with the sensitive millivoltmeter.

It is recommended that not only the sheet-to-sheet contact resistance is measured, using the specimens, but that the electrode to sheet measurements are also made by placing one test piece only between the electrodes. This method enables contact resistance measurements to be obtained up to 10 s.w.g., since now the question of deforming the sheet does not arise. Currents in the range of 10 to 20 amps. are used for the test, to obtain satisfactory deflections of the millivoltmeter.

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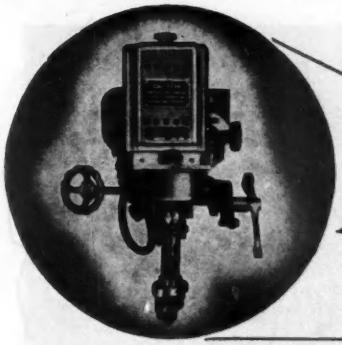

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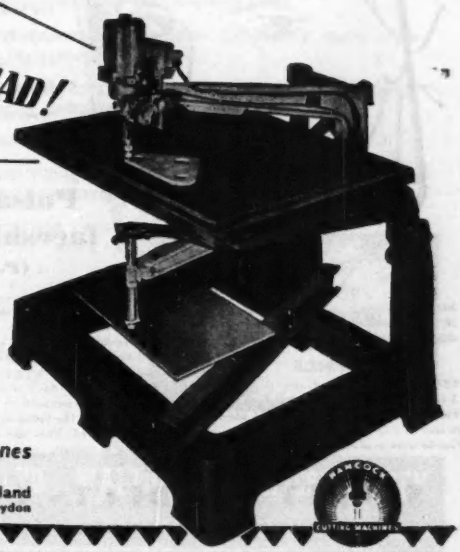

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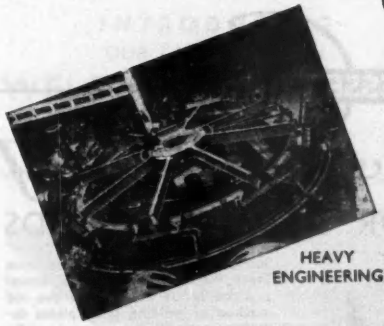

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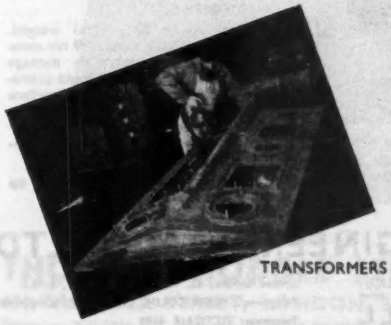

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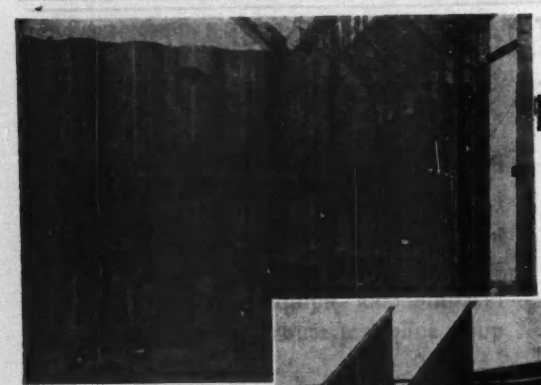

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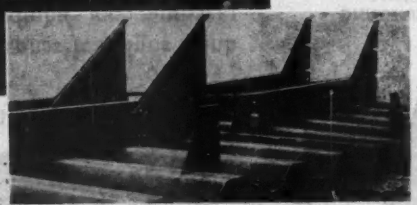

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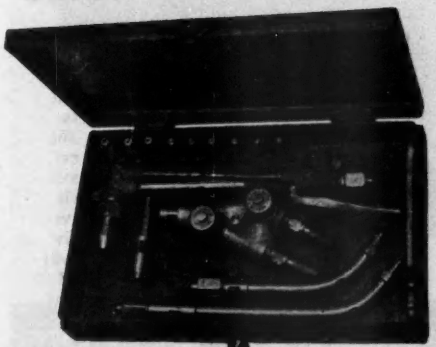

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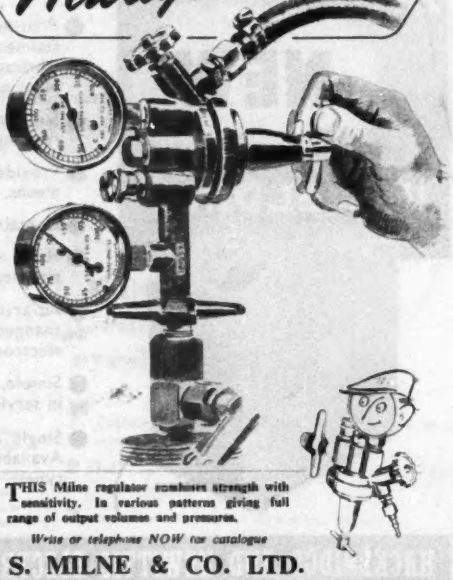

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